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by Laurence R. Young, David M. Green, Jerome I. Elkind, and Jennifer A. Kelly

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SUMMARY

The human operator in a manual tracking task is known to change his control characteristics to adapt to particular controlled element dynamics, input characteristics and task requirements. This report describes an experimental investigation of human adaptive control following sudden changes in gain or polarity of the controlled element in a closed-loop tracking task. The experiments used primarily simple position control to determine lower bounds on the adaptation process. Random inputs were tracked under pursuit and compensatory single-axis displays.

Average error waveforms following controlled element transitions reveal the time course of adaptation. The average waveforms and data on time necessary to cancel the errors following transitions indicate some of the factors affecting the adaptation process. Complexity of the transition and form of the initial error are both important in changing the operator's control law.

Times necessary for adaptation to changes in simple tracking conditions are quite small. Human operator control adaptation generally occurs in 0.4-0.8 sec. following a controlled element change, and the resulting error is usually reduced to its asymptotic level in 1-3 sec. following transition.

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SECTION I

INTRODUCTION

The need for adequate analytic descriptions of the performance of the human operator in a tracking task was recognized during World War II, in connection with fire control problems. Tustin[1] first used the techniques of servomechanism theory to fit a linear description to the operator, and Sobczyk and Phillips[2] used such techniques in finding the optimum "aiding constant" for handwheel tracking. Theoretical and experimental support for assisting the human with aided tracking was generated by Weiss[3] and investigators at the Franklin Institute.[4] Thereafter, use of linear process identification techniques by Russell[5], Krendel[6], Elkind[7], and Goodyear Aircraft[8] led to human operator models which account for most of the operator's response under various conditions of input characteristics and controlled element dynamics. Investigation of different control dynamics and display conditions by Birmingham, Taylor and Chernikoff[9] indicated their effect on tracking error level. Most of the relevant studies prior to 1957 are discussed in the thorough review by McRuer and Krendel.[10]

There have been several distinct fields of effort in recent work on human operator descriptions. Ashkenas and McRuer[11] and Creer and Sadoff[12], have studied aircraft handling qualities and pilot opinion, correlating it with models for pilot control operation. The importance of the psychological refractory period, early emphasized by Craik[13] and Hick[14], has led to investigation of discontinuous models of the human operator by Bekey[15], Wilde and Westcott[16], and Naves[17]. The time-varying characteristics of the human operator have provided another field of interest. Sheridan[18], and Ornstein[19] have measured slowly varying transfer functions, and Elkind[20] has developed a more rapid identification technique for this purpose. Sadoff[21] has investigated the pilot's ability to control a craft through a simulated failure of part of the system. The present research continues along the line of studying the time-varying characteristics of the human operator under controlled element changes.

Although human operator characteristics under steady-state conditions have received much attention, very little work has been done concerning the dynamic process of adjustment of human operator characteristics in changing from one control situation to another. This report describes an experimental program aimed at investigating the adaptive characteristics of manual tracking. Extensions of human operator tracking descriptions to include his adaptive behavior would be of significant value to engineers concerned with the design of modern vehicles and to those interested in the entire field of adaptive control.

In our approach we have limited ourselves to investigation of a single aspect of the general adaptive situation, namely the ability of the human operator to adapt his behavior following sudden changes in the controlled element dynamics.[22]

For all experiments discussed in this report the subjects manipulated a light control stick to track a simulated target displayed visually under both pursuit and compensatory situations. At some point during the tracking experiments, and without warning to the subject, the controlled element dynamics were suddenly switched to a new value. Analysis concentrated on detailed investigation of the time course of the operator's response during the instants following the controlled element changes. Most of the experiments discussed in this report used a simple gain as the controlled element in order to uncover basic limitations in the human adaptive process.

We have attempted to answer two sets of questions by means of these experiments:

1. How fast can the adaptation process take place? What factors determine the speed of adaptation, and what is the lower time bound that one can expect?

2. What is the process by which the human adapts to a new control mode? What information does he use to determine when a change in his characteristics is required, which parameters of his control characteristics can he vary easily and rapidly, and which does he find more difficult to change? In what order does he change these parameters?

Answers to these questions would provide the key to the nature of human adaptive tracking.

SECTION II

APPARATUS

Fig. 1 shows a subject at the controls. He is seated in a small cubicle six-feet high, two-and-one-half-feet wide, and six-feet long. Placed on the wall directly in front of him is an 11 x 14 inch oscilloscope positioned at eye level and approximately 36-inches from the subject. The visual indicators on the display are a one-half-inch diameter circle and a small dot. For pursuit tracking the target signal, or input, is the horizontal displacement of the circle and the subject controls the horizontal position of the small dot. For compensatory tracking, the circle remains stationary in the center of the oscilloscope and the horizontal displacement of the small dot is equal to the difference between the input and the subject's response.

The subject makes his response by moving a light control stick which protrudes through a circular hole in the right-arm rest of a student's chair on which the subject is seated. The control stick is spring restrained and easily manipulated by a wrist movement requiring one pound for maximum deflection. The stick can be moved approximately ± 45 degrees from its upright position. The right and left movements of the stick provide the voltages for the input to the controlled dynamics. The stick is free to move in the forward and back directions as well as left and right, but only the latter motion effects the response signal.

A special display card masks all but part of the oscilloscope face, showing only a small rectangular segment of the screen - 3-inches in height and 14-inches in width. At the edge of this mask an arrow marks the horizontal center of the rectangle. Other indications occur at three and five inches to the left and right of the center. These marks are included to reduce any autokinetic effects in the tracking cubicle. The cubicle is lighted indirectly from a fluorescent lamp positioned about one-foot above the oscilloscope. The walls of the cubicle are painted dull gray to reduce reflection from the face of the display. The display uses mechanical choppers in X and Y directions for presentation of the two visual indicators on the display oscilloscope.

Fig. 2 is a functional block diagram of the entire experimental apparatus. The random continuous input signals, consisting of rectangular noise spectra, were stored on magnetic tape. (For the "step" experiments the input was the sum of square waves from square wave generators). The response signal from the subject's control stick was fed to an Electronic Associates Incorporated TR-48 analog computer. The TR-48 computer is programmed to give two parallel channels of control modes. Each channel may be placed in any one of 10 modes by a selection of switches. While the subject is tracking with certain control element dynamics in one channel, the output of the other channel is not connected to the response dot. A selector switch for the second channel may be set to determine the dynamics of the next tracking mode. The "change channel switch" is under the control of the experimenter, and changes control to the alternate channel when conditions required by the channel coincidence and input rate threshold circuits are satisfied. Once the change occurs the first channel is free and may be set to the next tracking mode. Thus for any experiment twenty different modes of the controlled element are readily available for selection by the experimenter.

The channel coincidence circuit is included to prevent the occurrence of discontinuities at transitions. This circuit closes a relay only when the absolute value of the difference between the active and inactive channel outputs is close to zero. This assures that when a transition between channels occurs there can be no jump in the position of the response dot, which might alert the subject to a change in controlled element dynamics. The input rate threshold circuit prevents transitions from occurring at times when the input is almost stationary. If such were the case, no significant immediate error increase would occur despite a change in controlled element dynamics. In addition, for the average response computations, the input rate threshold circuit is made unidirectional so that the errors following the transition will all be of the same phase.

Pen recordings of the input and response of the inactive as well as the active channel were taken to ascertain at what point the subject ceases tracking according to the previous mode of the controlled element. The error is also recorded on the pen recorder as is its absolute value filtered by a simple 0.25 sec. low-pass filter. This latter quantity was used in our estimate of adjustment time. For computation of the average error following transitions, the tracking error and the controlled element mode indicator were recorded and later played into a Digital Equipment Corporation PDP-1 digital computer.

The display in Fig. 2 is shown for pursuit tracking. For compensatory tracking the dot is driven directly by the error and the circle remains stationary at the center position.

Detailed diagrams of the analog computer programs are given in Appendix A of this report.

SECTION III

EXPERIMENTAL RESULTS (I) - ADJUSTMENT TIMES

3.1. Adjustment Times - Random Input (R.64)

In an effort to set bounds on the adjustment time following changes in control gain and polarity, as well as to determine those factors which contribute most heavily to determining the adjustment time, experiments were conducted on five trained subjects tracking under pursuit and compensatory situations. Each subject was scored on 180 transitions in pursuit and compensatory tracking. (Details of the experimental design and the scoring method are given in Appendix B). For each transition, adjustment time was recorded. These times were examined to determine the effect of the following factors:

1. Modality of display - compensatory versus pursuit.

2. The number of alternative modes of the controlled element dynamics - the control being switched among 2, 4, or 8 control settings in the course of an experiment.

3. The effect of the expected initial error introduced by the transition - as measured by the "relative difference" to be defined below.

4. The "complexity" of the transition - whether it consisted of a simple gain change or polarity reversal, or a combination of the two.

Summary tables of the adjustment times for the entire experiment are given in Appendix C. Only those results which prove to be interesting or significant will be discussed in this section.

The statistical tests used were all non-parametric. The reason for this was that the necessary conditions for the valid use of parametric tests are not fulfilled. In particular, partly for the reasons given below, the distributions were not normal. The test used was either the Mann-Whitney U Test for independent samples, or the Wilcoxon Matched-Pairs Signed-Ranks Test, depending on the data being compared. All significance levels quoted are for 2-tailed tests.

Before discussing the results, however, a word of caution concerning the definition of adjustment time is in order. Our criterion required the subject to reduce his error to three times his asymptotic tracking level and maintain this performance for a period corresponding to more than two full cycles of the highest input frequency (three seconds). In general this criterion agreed with our subjective appraisal of when the subject had "caught on" to the new control model and had further succeeded in reducing the large errors introduced at the time of transition and shortly thereafter. There were occasions, however, particularly for gain-decrease transitions, in which the error level never exceeded the criterion, forcing us to record the transition as having zero adjustment time. In other cases the absolute error would bounce back above the criterion level several times, yielding extraordinarily long adjustment times which perhaps did not fairly represent the "true state" of the human operator. Attempts to move the criterion level up or down all introduced more serious discrepancies between occasional indicated adjustment times and subjective evaluations of the state of the human operator. This type of measure appears to have an extremely large variance and makes it quite difficult to say much about the factors affecting adjustment time with any great degree of confidence. We have no assurance that any of the results found in this set of experiments would necessarily continue to hold true under a different type of criterion for measurement of adjustment time. With this warning, we can proceed to examine the results.

3.2 Display Modality and Number of Modes

The summary graph of Fig. 3 showing median adjustment times for all five subjects under all types of transitions indicates the superiority of the pursuit type display to a simple compensatory display for rapidity of adjustment to a controlled element transition. Analysis of the pursuit versus compensatory results of Tables C1-7 show significantly shorter adjustment times for pursuit tracking than compensatory tracking ($p<.02$). Fig. 3 also shows that for compensatory tracking the adjustment time is insensitive to the number of possible alternative control modes in the experiment. For pursuit tracking, however, the number of possible modes does indeed seem to affect the mean adjustment time, this time increasing with the number of alternative modes in the experiment. Although the increase in median adjustment time for pursuit tracking from 2 modes to 4 modes is rather small, the adjustment time for tracking under 8 alternative modes is significantly longer than for two modes ($p<.01$).

3.3 Expected Initial Errors--Relative Differences

The degree of difference between the new mode and the previous one is expected to be an important aspect of the control mode transition. The difference between two control modes is measured by the different effect on the response of the same input by the subject to the control stick, and is an indication of the initial error which would be displayed to the subject on his first movement following the transition. To quantify this notion, we define "relative difference" of the transition in the following manner: in a transition from Mode A to Mode B, the same subject movement which would cause a controlled dot response of 1 unit in Mode A now causes a movement of x units in Mode B. The relative difference is defined as the absolute value $|1-x|$. The relative difference of two modes is thus a ratio: the difference between a response in the new mode and what would have been expected in the old mode, divided by the response expected in the old mode. Thus, in a transition from +1 to +2, or any simple doubling of gain, x is 2 and the relative difference is 1. In a transition from -2 to +8, x is -4, and the relative difference is 5. Table 3.1 lists the relative difference for each of the gain transitions used in this experiment. Large relative differences correspond to control mode transitions which would tend to give large initial errors.

TABLE 3.1

THE RELATIVE DIFFERENCES OF THE GAIN TRANSITIONS

TYPE	TRANSITION		RD	TYPE	TRANSITION		RD
GAIN	+1	+8	7	REVERSAL	+1	-8	9
INCREASE	+1	+4	3	INCREASE	-1	+8	9
	-2	-8	3		-2	+8	5
	-1	-4	3		+1	-4	5
	-1	-2	1		+2	-8	5
	+4	+8	1		-4	+8	3
	+1	+2	1		+1	-2	3
	-2	-4	1				
GAIN	+8	+1	7/8	REVERSAL	-8	+1	1-1/8
DECREASE	+4	+1	3/4	DECREASE	+8	-1	1-1/8
	-8	-2	3/4		+8	-2	1-1/4
	-4	-1	3/4		-4	+1	1-1/4
	-2	-1	1/2		-8	+2	1-1/4
	+8	+4	1/2		+8	-4	1-1/2
	+2	+1	1/2		-2	+1	1-1/2
	-4	-2	1/2				
REVERSAL	+2	-2	2				
	-2	+4	2				
	+4	-4	2				
	-4	+4	2				

Fig. 4 is a graph of the median adjustment time as a function of the relative difference of transitions for pursuit and compensatory display modalities. The summary data for this plot is given in Table C8 of Appendix C. The pursuit data of Fig. 4a yields a significant correlation between adjustment time and relative difference. Those transitions which are expected to yield a large initial error tend to require a longer time before the error can be reduced to close to its asymptotic level.

The data for compensatory tracking shows a somewhat different trend with relative difference. The overall shape of the compensatory tracking curve does not exhibit the generally increasing shape of the pursuit data. From a peak at RD=1-1/8 the compensatory curve decreases generally until RD=2, where it begins to show a slight rise. An interesting observation for both pursuit and compensatory data is the relative decrease in adjustment times at RD=1 and RD=2, with respect to the trend of neighboring points.

3.4 Transition Complexity

The absence of a clear relationship between relative difference of a transition and the associated adjustment time stimulated a search for other characteristics of the transitions which would prove to be significant factors affecting adjustment time. We define the "complexity" of a transition in terms of the number of parameters of the controlled element dynamics which have been changed by the transition. For this simple position control experiment the only possible transitions were gain increases, gain decreases, simple polarity reversals, or combinations of polarity reversal and gain change. The transition complexity includes only two groups: simple one-parameter transitions consisting of gain change or polarity reversal, and complex two-parameter transitions consisting of both gain change and polarity reversal.

It was noted in Fig. 4 that the adjustment times for relative differences of 1 and 2 are appreciably below the trend of neighboring data points. Reference to Table 3.1 shows that all transitions with relative difference 1 are simple doubling of the control element gain and that all transitions of relative difference 2 consist of simple polarity reversal with no change in gain. Those transitions with relative difference close to 1 or 2, but involving a complex transition all show longer adjustment times than these simple transitions. (Since complex transitions generally tend to yield larger relative differences than simple transitions, the two measures are by no means independent).

To study the effect of transition complexity, the adjustment time data were grouped according to the following five transition classifications: gain increase, gain decrease, reversal, reversal increase, reversal decrease. The median adjustment times taken for all five subjects are shown in this form in Table C8 of Appendix C. Median adjustment times for each of the transition types for all subjects under 2, 4, and 8 modes switching experiments are illustrated in Fig. 5.

Complex transitions requiring the human operator to change both his gain and polarity lead to longer adjustment times than simple transitions requiring changes of either gain or polarity. This phenomenon holds true for pursuit as well as compensatory display modalities ($p<.0001$). Among other differences shown on Fig. 5 which have been found to be statistically significant are the following:

a. The relative adjustment times associated with the two types of complex transitions depend upon the display modality. For the compensatory display under combined 2, 4, and 8 mode experiments the reversal decrease transitions required significantly longer times for adjustment than the reversal increase experiments. ($p<.02$) (Median times 5.8 sec, 3.9 sec) For the pursuit display under the same experimental conditions, however, we find that the reversal decrease transitions take significantly less time for adjustment than the reversal increase transitions. ($p<.05$) (Median times 2.3 sec, 3.6 sec)

b. Transitions not requiring polarity reversals yield shorter adjustment times than those requiring a polarity reversal. This result is statistically significant in the compensatory 8 mode and 4 mode experiments ($p<.01$, medians 2.5, 4.4 for 8 modes; $p<.05$ medians 2.9, 4.4 for 4 modes) and in the pursuit 4 mode experiments ($p<.001$, medians 1.6, 3.1).

c. Under pursuit display conditions a simple gain increase requires a significantly longer adjustment time than a simple gain decrease ($p<.02$, medians 2.1, 1.5).

In general, although the large variance in the measure of adjustment time prevented the extraction of many apparent relationships, the partitioning of transition types according to complexity rather than by proportional difference was more successful in indicating some of the factors which affect adjustment time.

3.5 Step Input Experiments - Compensatory Tracking

A somewhat different approach to investigation of the adaptive process of manual control uses deterministic test input signals to probe the state of the pilot's adaptation at any given time. Since the desired or fully adapted response to these test signals is well-known, the degree of adaptation at any time following a controlled element transition should be determined by observing the response to such a test input and comparing it with the desired results. To this end we conducted a series of informal experiments in which the input consisted of an apparently random series of discontinuous jumps in the target position. The step response for the fully adapted case typically contained a reaction time of 0.2 to 0.4 secs. followed by a fast movement in the correct direction reaching approximately the correct amplitude after another 0.3 to 0.5 secs. When the controlled element gain was suddenly increased, the next step response would exhibit a large overshoot in the initial movement, generally followed by several alternating overshoots until the error was finally reduced to zero. (see Fig. 6) Succeeding step responses of the same gain level were composed of successively fewer response overshoots and occasional cautious undershoots, the operator soon becoming adapted to the increased controlled element gain and decreasing his own gain accordingly. Similarly, when the controlled gain was suddenly reduced, the step responses were initially too small in extent and many corrective movements were required to null the error. The subject once again would increase his gain appropriately, so that the succeeding step responses would consist of a single rapid movement requiring perhaps a secondary corrective response. In these experiments the gain was switched from +1 to +6 or from +1 to +11. As described in Appendix B, the performance criterion was the movement time (MT) from the subject's initial response until the error was reduced to below 0.1 inch and its rate to less than 0.5 inch per sec.

On the initial experiments with untrained subjects, we observed a fairly well-defined adaptation process manifested by a more or less exponential decrease of movement time with step number. The adaptation time appeared to spread over 7 to 15 steps following the gain transition, or approximately 15 to 30 sec. This extremely long adaptation time was apparently a result of lack of training. Fig. 7 shows the typical reduction of movement time for successive steps following a gain change for a better trained subject (four hours of training). After the first or second step the movement time remains relatively constant. This is true for both a high repetition rate of approximately 30 steps per minute and a low rate of approximately ten steps per minute.

The oscillographs of response and error indicate clearly that almost all of the adaptation takes place during the response to the first step, and by the second and third steps the trained subject responds in essentially a fully-adapted fashion. In general very little difference is noted between the reduction of movement time for high repetition rates and low repetition rates when we consider adaptation as a function of step number following a transition rather than as a function of time.

Because of the rapidity of adaptation to the step inputs as well as the ease with which the controlled element gain could be identified by the subject, the use of a step input as a probing function was discontinued in favor of the continuous pseudo-random inputs discussed above.

SECTION IV

EXPERIMENTAL RESULTS (II) - THE ADAPTATION PROCESS VIA AVERAGE ERROR WAVEFORMS

Average error waveforms following specific types of transitions are calculated to reveal the processes by which the human operator adapts to changes in controlled element dynamics. They are intended to bring out those features of the adaptation process consistent in almost all occurrences of a particular type of transition. The averages may be assumed to reflect the basic behavior pattern of the subject in the task of (a) detecting a change in controlled element dynamics (b) correctly identifying the nature of this change and (c) adopting a new control law, consistent with the new controlled element dynamics.

The results of this section are presented as a series of curves of calculated error waveform averages rather than a table of numbers derived from these curves. The average error waveform can, of course, show what characteristics of the adaptation process lead to the adjustment time differences discussed in the previous section. Details of the experimental design are given in Appendix B.

Variation in the calculated average waveform is shown by means of a typical example in Fig. 8. The dotted line shows the computed ensemble average of errors following a transition from +2 to -8. Averages are calculated at 0.04 sec. intervals. The standard deviation of the 19 individual transitions making up the average was calculated at 0.25 sec. intervals, and is shown by vertical lines on the graph of Fig. 8. The standard deviation of the average is $\sigma_d/\sqrt{N}$ where σ_d is the standard deviation of the original distribution and N is the number of samples in the averaging process. For this case of N = 19, plus and minus one standard deviation of the average error waveform curve is shown at each sample point by the height of the rectangles in Fig. 8.

4.1 Average Error Waveforms Corresponding to Conditions of the Adjustment Time Experiment

The average error curves of Figs. 9 and 10 correspond to some of the transition types considered in the adjustment time experiment for the pursuit and compensatory displays. The input signal was the high frequency spectrum (R.64), and all transitions were taken during two mode experiments. The curves of Fig. 9 were recorded for tracking with a pursuit display, and show certain error characteristics associated with the type of transition. As described in Appendix B, all curves are compensated for the average error contributed by switching at similar phases of the input each time. The discontinuities at the beginning of the average curves are a result of an initial delay in the computer program.

For a simple gain increase (Fig. 9a) the error reaches a peak very rapidly and reverses to an overshoot on the other side of the zero line, the error oscillation disappearing after this second peak. For a gain decrease, on the other hand, (Fig. 9b) the error rises more slowly, taking a longer time to reach its rather flat peak, and then gradually decreasing to its asymptotic level. The negative error portion of the curve correlates with the input, and shows that the response was still "falling behind" as a result of low gain for 2 sec. In the case of a polarity reversal (Fig. 9c) the error rises rapidly for a considerably longer time period than in the case of a gain increase, and then descends sharply from a well-defined peak. The complex transitions seem to include some of the characteristics of the two simpler types of transition in the adaptation process. Thus, for a polarity reversal and gain increase (Fig. 9d) the average error rises sharply to a first peak which is larger and later than for a simple gain increase, and then reverses direction to reach a second peak on the opposite side of the error base line. This waveform thus includes both the initial large error and time delay associated with the polarity reversal and the double-peak overshoot associated with the simple gain increase.

In a similar manner the average error waveform for a reversal-decrease transition (Fig. 9e) contains characteristics of both the simple reversal and the simple gain decrease. After rising to a delayed initial peak, as in the case of the simple polarity reversal, the error waveform then decreases slowly to its asymptotic level just as in the case of the simple gain decrease.

Pursuit-Compensatory Comparison

Some of the same types of transitions are shown for compensatory tracking in Fig. 10. The simple polarity reversal of Fig. 10a takes longer to reach its peak than the corresponding pursuit waveform (Fig. 9c) and leads to longer adjustment times. The transition waveforms of Fig. 10b, and Fig. 10c help explain the relationship of adjustment times for complex transitions under pursuit and compensatory tracking discussed in connection with Fig. 5.

For the compensatory reversal-increase (Fig. 10b) the maximum error is large, but once having been reached its peak decreases rapidly without much significant overshoot. The reversal-decrease transition (Fig. 10c) yields an average error waveform which is noticeably spread out in time. It exhibits a slow accumulation of error to a broad peak and gradual error reduction, yielding a longer adjustment time than the reversal-increase.

In contrast to the compensatory result, however, for the pursuit display the consistent overshoot of the reversal-increase transitions give it longer adjustment times than the reversal-decrease transitions. The pursuit display waveforms also show that the complex transitions (Figs. 9d, 9e) yield error waveforms which take longer to reach their asymptotic level than the simple transitions of Figs. 9a, 9b, 9c. These findings are in agreement with the simple-complex adjustment time relationships shown in Fig. 5.

The average error curves of Figs. 9 and 10 show the general form of the adaptation process for various types of controlled element transitions, and are presented as an aid to interpretation of the results of the adjustment time experiments discussed in Section III. For a detailed investigation of the adaptation process, however, we shall examine average error waveform curves taken under conditions of a low-frequency input spectrum (R.24), since they reveal greater consistency in the adaptation process than the high frequency input experiments discussed above.

4.2 Average Error Waveforms Following Transitions for Compensatory Tracking at Low-Frequency Input.

Polarity Reversal

Average error waveforms for two trained subjects following a control polarity reversal are shown in Fig. 11. A simple polarity reversal will convert the stable closed-loop negative feedback system into an unstable positive feedback system until the human operator adapts by changing his own control polarity. The curves of Fig. 11 show that the tracking error increases rapidly in the moments following polarity reversal as each attempt to decrease the error merely increases it further.

This increase in error reaches a sharp peak on the average at 0.5 sec. following the transition, indicating a reversal in the subject's control. Following this adaptation the error is decreased rapidly to a low level within the next second.

A typical time tracing showing subject's response and error signals prior to and following a polarity reversal is given in Fig. 12. The upper channel giving input and response shows that following the polarity reversal the response began moving in the wrong direction. The error increased sharply after 0.3 sec. and then was reduced abruptly at 0.7 sec. as the subject reversed his own polarity and moved the control stick in the correct direction. The second channel shows what the response would have been if the system were in its pre-transition mode, (i. e. a gain of +2) and demonstrates that for the first 0.3-0.6 sec. the response of the inactive channel followed the input very closely. This indicates that during this early period following the transition, the subject continued to track as though the polarity of the control were still positive, and he had not identified the transition.

The third channel represents the difference between the subject's response and the input. This is the error displayed on the oscilloscope in the compensatory tracking task, and also averaged in the average error waveform computation. Its peak clearly demonstrates that adaptation had begun by 0.7 sec. following the transition.

The fourth channel is a recording of the absolute error of tracking passed through the low-pass filter with time constant of 0.25 sec. As described previously, this channel is used to estimate adjustment time. In this case using a criterion of 3/4-inches, the estimated adjustment time is 1.3 sec.

Gain Increase

Fig. 13 shows average error curves for two subjects in compensatory tracking following increases in the controlled element gain from +2 to +8. The initial effect of the gain increase is an immediate increase in error. As the subject seeks to eliminate this error, he causes the reponse to overshoot and quickly produce an error of the opposite sign. Notice that on the average the first corrective movement took place before 0.3 sec. for both subjects. Of particular interest in these figures is the observation that in neither case is the subject's second error peak of higher amplitude than the first one. An unadapted control loop would exhibit oscillations of increasing amplitude when its gain was multiplied by a factor of 4. Thus, some adaptation must have taken place before the second peak in each case, and undoubtedly by the time the average error has crossed the base line. For both subjects this average error curve crosses the base line at approximately 0.5 sec. The average error decreases to its asymptotic level sometime between 1 and 2 seconds following the transition. Notice that the average error for subject GK does not show the marked overshoot seen for subject RB.

Fig. 14 shows an actual time tracing prior to and following a typical gain increase from +2 to +8 for subject RB, of the type summarized in the average error curve of Fig. 13. The initial result of the gain increase is an overshoot in response lasting for 0.2 to 0.3 sec. The corrective movement made in an effort to reduce this error results in an overshoot to the opposite side which peaks at 0.8 secs.

The amplitude of the overshoot to the opposite side is smaller than the original error the subject was attempting to nullify, showing that he had achieved a significant amount of gain reduction by the time this second movement was completed. Following the second peak the error is gradually reduced and the effects of the transition in controlled element are difficult to see after a little more than 1.5 sec. following the transition.

Gain Decrease

The effect of a simple gain decrease in the controlled element is not to introduce any instability in the closed-loop performance, but simply to lower the open-loop gain to the point where system performance becomes very sluggish. Such a transition produces very small initial error when the input signal is of low frequency and would cause no serious consequences in system performance if adaptation were not to take place. The average error following such transitions from +8 to +2 for both subjects is shown in Fig. 15. Notice that the error increases slowly, reaching a rather flat peak at 0.7 to 0.8 sec. for both subjects. The error then returns very gradually toward zero, crossing the axis at 1.3 sec. for subject RB and not until 1.8 sec. for GK. The upper channel of Fig. 16 shows that following the transition the response lags the input, accumulating error slowly for 1.0 sec. and then gradually decreasing the error during the next 1.5 sec.

Reversal Increase

Average error waveforms following reversal increase transitions are shown in Fig. 17. It is of interest to compare these average error curves with those of Fig. 13, for the same two subjects following a simple gain increase transition. After the complex transition (+2 to -8) the average error curves rise very steeply, yielding larger peak errors than for any other type of transition. For both subjects the time of occurrence of this first peak for the complex transition (0.4 to 0.5 sec.) is slightly longer than the time of occurrence of the first peak for the simple gain increase (0.2-0.3 sec.) Following this first peak, which represents adaptation to the polarity reversal, the average error waveform curves for both subjects show a similar time course for adaptation to the complex gain increase as for the case of a simple gain increase. For RB the error shows a second overshoot of lower amplitude than the first. Subject GK once again shows little tendency toward oscillatory error, and his average error waveform decreases gradually toward its asymptotic level.

A typical transition record for this type of control change is shown in Fig. 18. For the first 0.4 sec. following the transition the response diverges from the input. When a polarity reversal is finally made, the gain remains somewhat elevated, leading to the secondary peak at 0.8 sec., and final gain reduction to a stable level reached after approximately 1.5 secs.

Reversal Decrease

The final type of controlled element transition considered is a reversal decrease from -8 to +2. The average error waveforms of Fig: 19 show a very different type of behavior from the reversal increase averages of Fig. 17. Following a reversal decrease the error increases slowly for a fairly long period despite the positive feedback nature of the control loop. The average time of adaptation to the polarity reversal as shown by the time of the rather broad peak in the average error curve is approximately 0.8 sec. following the transition. Following this peak in the average error, the adaptation process proceeds in a smooth fashion reaching the steady average error level sometime after 1.5 secs. following the transition. The long, low overshoot of the average error from 2 to 5 secs. following the transition is input dependent, and once again shows the continued existence of a small average error in phase with the input as the response continues to lag behind the input until the subject's gain is increased.

In the reversal decrease time tracing of Fig. 20, it is seen that the error showed an accelerating increase for 0.6 sec. before the subject reversed direction of the control stick. Under the decreased gain, the error took 1.3 sec. to cross the base line, and the response lagged the input for the next three seconds, leading to a long adjustment time.

4.3 Average Error Waveforms Following Transitions for 8-Mode Versus 2-Mode Switching Conditions

All of the above average error waveform curves were derived from experiments conducted under compensatory display conditions in which the controlled element was merely switched back and forth between two modes. To see whether the rapid adaptation observed under these conditions resulted from the simplicity of the "back-and-forth" nature of the controlled element switches, the experiments were repeated under the 8-mode switching conditions, in which the controlled element dynamics were permitted to change from a base condition of +2 to any one of the other seven possible gains in a random sequence. Average error computation following transitions in the 8-mode experiment for compensatory tracking showed no important changes in the shape of the error curve, and most important, no apparent lengthening of the adaptation or adjustment process as a result of increasing the number of possible modes into which the controlled element could be switched. Fig. 21 is an example of a comparison between average error curves taken under 8-mode conditions and the comparable curve for the 2-mode switching experiment. For a +2 to +8 transition, we notice that aside from a possible slight elevation in the size of the second overshoot under 8-mode switching conditions, the error curves are quite similar for 2- and 8-mode conditions.

4.4 Average Error Waveforms Following Transitions With Velocity Tracking

The experimental results referred to above were based on tracking experiments wherein the controlled element consisted of a simple amplifier whose gain and polarity could be changed. In practical tracking situations the controlled elements generally have dynamic characteristics which affect the closed-loop performance, and for which the human operator compensates in his role as a controller. To investigate the extent to which the results obtained on the simple proportional control experiments might be generalized to include the problem of adaptation under complexed dynamics, we performed several preliminary experiments involving transitions among different types of controlled element dynamics. The average error waveform curves shown in Fig. 22 both represent the adaptation process following a simple polarity reversal in the controlled elements. The curve of Fig. 22b was derived from the experiment in which the controlled element was an integrator, and the transition consisted of a reversal of 4/s to -4/s. The subject had received training under the velocity tracking conditions prior to the experiment, and his steady-state error was of approximately the same magnitude as for position control tracking. When the average error waveform of Fig. 23b is compared with that of Fig. 23a, which shows the same subject's performance for polarity reversal under position control, the differences are quite apparent. The error initially rises at approximately the same slope for both types of control, as a result of the uncompensated polarity reversal. Whereas the error reaches its peak at 0.5 sec. under position control, the peak does not occur until 0.7 sec. following the transition for velocity control. By this time the average error has risen to nearly 1-1/2 times the amplitude of the peak average error for position control. Following this peak the large error is reduced gradually through the integrator in the forward loop, not reaching its steady-state level until nearly 2 sec. following the transition. Although the general shapes of the two average error waveform curves are similar, the time course for the adaptation process with velocity control was apparently longer than the similar process under position control.

SECTION V

INTERPRETATION OF RESULTS

Before attempting to interpret the experimental results in terms of the basic adaptation process of the human operator, it is instructive to consider the consequences of a non-adaptive human operator model under changes in controlled element dynamics.

5.1 Transfer Function Models

For a simple compensatory tracking task with controlled element of unity gain, Elkind generated parameters for a human operator transfer function of the form

$$\frac{Ke^{-\tau s}}{(T_I s+1)(T_n s+1)}$$

The parameters vary with the frequency characteristics of the input spectrum, and were selected by finding the "best fit" of the assumed transfer function form to the experimental data. The R.24 rectangular spectrum used in the present investigation yielded the values:

$$\begin{aligned} K &= 40 \\ \tau &= 0.1 \\ 1/T_I &= .3 \\ 1/T_n &= 6.2 \end{aligned}$$

The closed-loop root locus for such a transfer function is sketched in Fig. 23, using a first Pade approximation of the form

$$e^{-\tau s} \approx \frac{-(\frac{\tau}{2}s-1)}{(\frac{\tau}{2}s+1)}$$

Two closed-loop poles cross the $j\omega$ axis and move into the right-half plane for open-loop gain greater than K= 40. This is to be expected, since Elkind selected his parameters for low frequency fit and marginal closed-loop stability, placing two closed-loop poles on the $j\omega$ axis.

Let us assume that the actual closed-loop system is stable and very lightly damped, with damping ratio $\zeta = 0.2$. This puts the "base condition" dominant poles at $s = -1.2 \pm j\ 5.7$ as shown in Fig. 25. The open-loop gain placing the poles in this position is K =20.

With this assumption for the poles in the base condition we may investigate the effect on closed-loop performance of open-loop gain changes. Doubling the gain of the controlled element without any change in the human operator transfer function would place the dominant poles almost exactly on the imaginary axis, at $s = \pm j\ 7.5$. The resultant error would oscillate at a frequency of 1.2 cps. Gain increase by a factor of four would move the poles into the right-half plane at $s = 2 \pm j\ 9.7$. The transient error would exhibit unstable oscillations of frequency 1.5 cps and a growing exponential envelope $e^{+t/\tau}$ time constant $\tau = 0.5$ sec.

Decrease of gain by a factor of four would move the dominant poles closer to the negative real axis, at $s = -2.9 - j\,1.6$. This corresponds to an increase of the closed-loop damping constant from 0.2 to 0.87, leading to a sluggish response.

For consideration of the effect of polarity reversals the root locus for negative values of K is drawn in Fig. 24. The dominant pole locus is on the real axis, crossing into the right-half plane at $K = -1.02$. The unadapted pole position for a simple polarity reversal is at $s = +2.8$, representing an unstable system with time constant 0.36 sec. For gain $K = -80$, (-4 times the base condition) the pole moves out to $s = 6.3$, corresponding to an unstable system with time constant 0.16 sec.

The hypothetical post-transition pole positions are based on the normal tracking behavior - with no adaptation assumed. Furthermore, they do not take into account the fact that the high frequency errors following transition might appear to the subject as a higher frequency input causing him to lower his gain and broaden his tracking bandwidth.

(Note: The concept of moving poles is not to be interpreted in a rigorous mathematical sense, but merely indicates the relationship between open-loop gain and system stability, as commonly used in engineering practice.)

Fig. 25 summarizes the dominant pole positions that would eventually be reached following the gain and polarity transitions investigated experimentally, assuming the human operator transfer function was valid and remained unchanged following controlled element transitions. These pole positions determine the behavior of the tracking error in the moments after transition but prior to any adaptation. Therefore, they indicate the type of information available to the subject, from which he must form his identification of the controlled element change.

5.2 Summary of Experimental Results

The preceding section indicates the effect of total absence of adaptation to controlled element transitions. By listing some of the experimental results concerning the way the closed-loop system does exhibit adaptation we may form hypotheses on the nature of the adaptation processes. The major experimental results are:

<u>For Compensatory Tracking</u>

1. Complex transitions lead to longer adaptation and adjustment times than simple transitions. Adaptation to the polarity and gain changes appear to be separate processes.

2. Of the two types of complex transitions, reversal decreases lead to longer adaptation times and adjustment times than reversal increases.

3. Of the simple transitions, adaptation is faster for polarity reversals and gain increases than for gain decreases - although adjustment times are about equal.

4. The number of alternative modes in the experiment has no effect on adjustment times.

5. Over much of the range investigated, adjustment times decrease with increasing relative difference of the transition.

For Pursuit Tracking

1. Complex transitions lead to longer adaptation and adjustment times than simple transitions.

2. Of the two types of complex transitions, reversal increases lead to longer adjustment times than reversal decreases.

3. Under all types of transitions pursuit tracking yields shorter adjustment times than compensatory tracking.

4. Adjustment times increase with the number of alternative modes in the experiment.

5. Adjustment times generally increase with increasing relative difference.

5.3 The Adaptation Process

It is helpful once again to consider the adaptation process as consisting of three necessary phases - even if it may not be possible to differentiate among them experimentally. The first of these is detection, or recognition that a change in the system performance has occurred. Once having detected a change, the subject must correctly identify the nature of the change, and therefore adopt a new control strategy consistent with his identification. Since we have no way of determining when the subject has noticed these changes, we must attempt to deduce detection from his control responses. Thus detection is indicated by any change from the pre-transition mode of control, and identification is indicated by the occurrence of a response consistent with the new controlled element dynamics. Adaptation consists of both detection and identification.

Once having adapted, however, the subject must still reduce the rather large errors which may have been built up in the interval between transition and adaptation. The reduction of the error composes the adjustment phase, and leads to the definition of adjustment time in terms of reduction of error to some criterion level.

The different types of transitions, display modalities and number of modes may be examined in terms of their effect on each of the phases of the adjustment process.

Information available for detection and identification is simply the error signal for compensatory display, whereas the response signal is directly shown for the pursuit display Since detection and identification based on the response display are direct for the simple position control, it is reasonable to find pursuit adaptation times shorter than compensatory adaptation. The adjustment process of reducing accumulated error thus takes on greater relative importance in the pursuit display. For the compensatory display the detection and identification of a control transition based on the error signal (contaminated with "noise" in terms of the presence of an input component) is a more difficult task, and these phases form a significant part of the entire adaptation and adjustment process.

The result showing that the number of alternative modes has no effect on adjustment time for compensatory tracking is contrary to the predictions of a detection model for simple mode switching. We must conclude that for compensatory tracking, even after considerable training on the possible control gains, the subjects do not appear to be mode switching, and are therefore not affected by the number of alternative control gains. In pursuit tracking, however, in which detection is considerably easier, the increase of adjustment time with number of alternative modes may indicate a certain amount of mode switching behavior. Thus in the two alternative pursuit cases the subject would merely detect any change in controlled element dynamics and he could rapidly change his own control characteristics to the correct alternative mode.

The relative difference of transitions is a measure of the ease of detection, since large relative differences yield large initial errors which should be easily detected. Large relative differences also tend to increase the adjustment phase, however, since large transition errors may take longer to reduce than small ones. Thus for compensatory tracking, where the detection-identification phase is difficult it would be expected that the effect of transitions with larger relative differences would be to shorten the adaptation times, and thereby perhaps shorten adjustment times. In agreement with this prediction, the average error waveforms of Figs. 13 and 15 show shorter adaptation times for $+2 \rightarrow +8$ than for $+8 \rightarrow +2$, and Figs. 17 and 19 indicate shorter adaptation times for $+2 \rightarrow -8$ than for $-8 \rightarrow +2$. Furthermore, the adjustment times for compensatory tracking generally decrease with increasing RD over the range 1-1/8 to 3, as shown in Fig. 4 and discussed in Section III.

The effects of relative difference of transitions on pursuit and on compensatory tracking are expected to be quite different. Since detection and identification are so simple in pursuit, the easier detectability of larger RD transitions should not have much effect on the adaptation process. The effect of large initial errors in increasing the adjustment phase assumes relatively more importance therefore, and predicts generally increasing adjustment time with RD. The average error waveforms of Fig. 9 show that for the pursuit display the adaptation times are about equal for $+2 \rightarrow +8$ and $+8 \rightarrow +2$, and also for $+2 \rightarrow -8$ and $-8 \rightarrow +2$. Reference to Fig. 4 and the accompanying discussion in Section III demonstrates a significant positive correlation between adjustment time and relative difference for the pursuit display, in contrast to the data for compensatory tracking.

The dual effect of increased initial error leading to easier detection and identification, but longer adjustment, helps interpret the marked difference between the two types of complex transitions under pursuit and compensatory tracking. The reversal increase has a large RD and yields an initial relative error four times as large as the reversal decrease. The reversal increase would therefore be expected to lengthen the adjustment phase in both pursuit and compensatory displays, but significantly shorten the detection-identification phase in the compensatory case. Fig. 5 clearly shows that the reversal increase yields longer adjustment times for the pursuit display and reversal decrease yields longer adjustment times for the compensatory display. Figs. 9d and 9e demonstrate by means of average error waveforms that the adaptation times are equal for $+2 \rightarrow -8$ and $-8 \rightarrow +2$ transitions under the pursuit display. The differences in adjustment times must therefore be a result of a longer adjustment phase for $+2 \rightarrow -8$, although this is not seen in the average error. Figs. 10b and 10c, showing average error waveforms under compensatory tracking, indicate a much longer adaptation time for $-8 \rightarrow +2$ than for $+2 \rightarrow -8$, confirming the effect of small initial errors lengthening adaptation time.

Perhaps the most interesting results generated by this investigation concern the adaptation to complex transitions, involving both polarity reversal and gain change. Adjustment time data show that a longer interval is required to adjust to complex transitions than simple transitions - especially under a compensatory display. Average error waveforms for compensatory tracking indicate that the adaptation process to a complex transition resembles two separate sequential processes - first a polarity correction and then a gain adjustment. Since there were only two parameters to be varied in this simple control it is dangerous to generalize from this evidence. The tentative interpretation, however, would rule out mode switching or continuous gain adjustment as the basis of the adaptation process. Rather, it suggests a two-stage process in which the subject first corrects polarity if necessary, and then increases or decreases gain if necessary.

On the basis of these interpretations of our experimental results, and use of the information that a tracking model yields on the unadapted behavior, we can hypothesize an adaptive model. The root locus argument indicated that the first transition error would yield unstable oscillations for gain increases greater than double, heavily damped response for gain decreases, and positive feedback instability for polarity reversals unless the gain were reduced by 95 percent.

A model to perform the required adaptation can be conceived to operate on error alone, or on error and some proprioceptive information on wrist movement. The general behavior of the error following a transition is described by the location of the system poles in the s-plane, as discussed in the beginning of this Section. Thus, if on the last response the error kept its same sign and increased, then a polarity reversal should be expected. If the sign of the error changed but its magnitude increased, then the polarity is probably correct but the gain may be too high. Finally, if the error magnitude decreased only slightly on the last response, then a controlled element gain decrease should be expected. Naturally, each of these observations is hampered by the presence of noise in the form of system input - and some redundant observations may be necessary before changing the control parameters.

An extension of this investigation to include transitions with more complex controlled element dynamics is under way. The average waveforms of Fig. 22 show that the adaptation process for a specific type of transition is lengthened when the controlled element is a pure integrator, despite good steady-state equalization by the operator. This result indicates that further research must be done on the nature of the human operator adaptation process with complex dynamics. The results presented in this report represent lower bounds for adjustment times and the adaptation process in an idealized situation.

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FIG. 1 PHOTOGRAPH OF SUBJECT AT THE CONTROLS

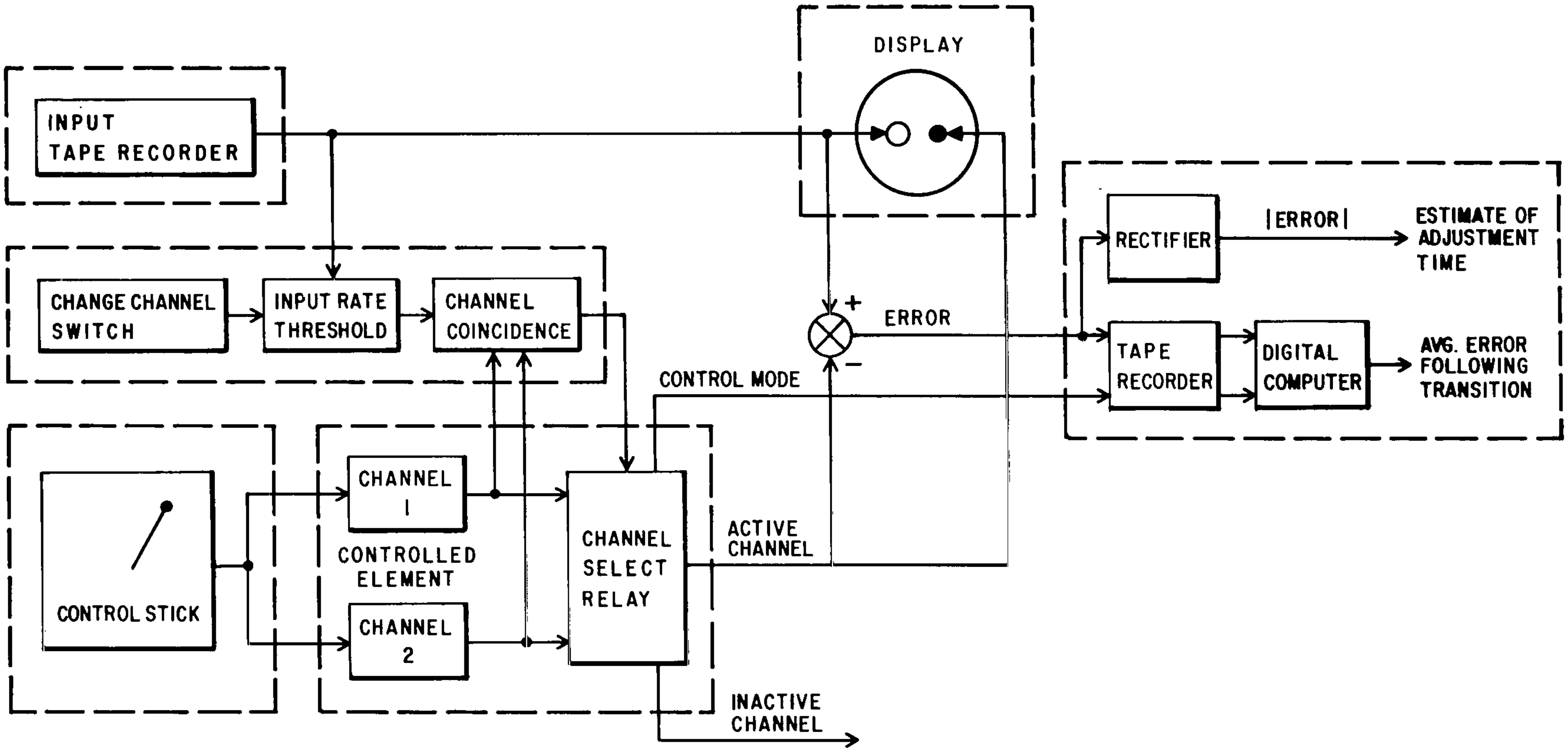

FIG. 2 FUNCTIONAL BLOCK DIAGRAM

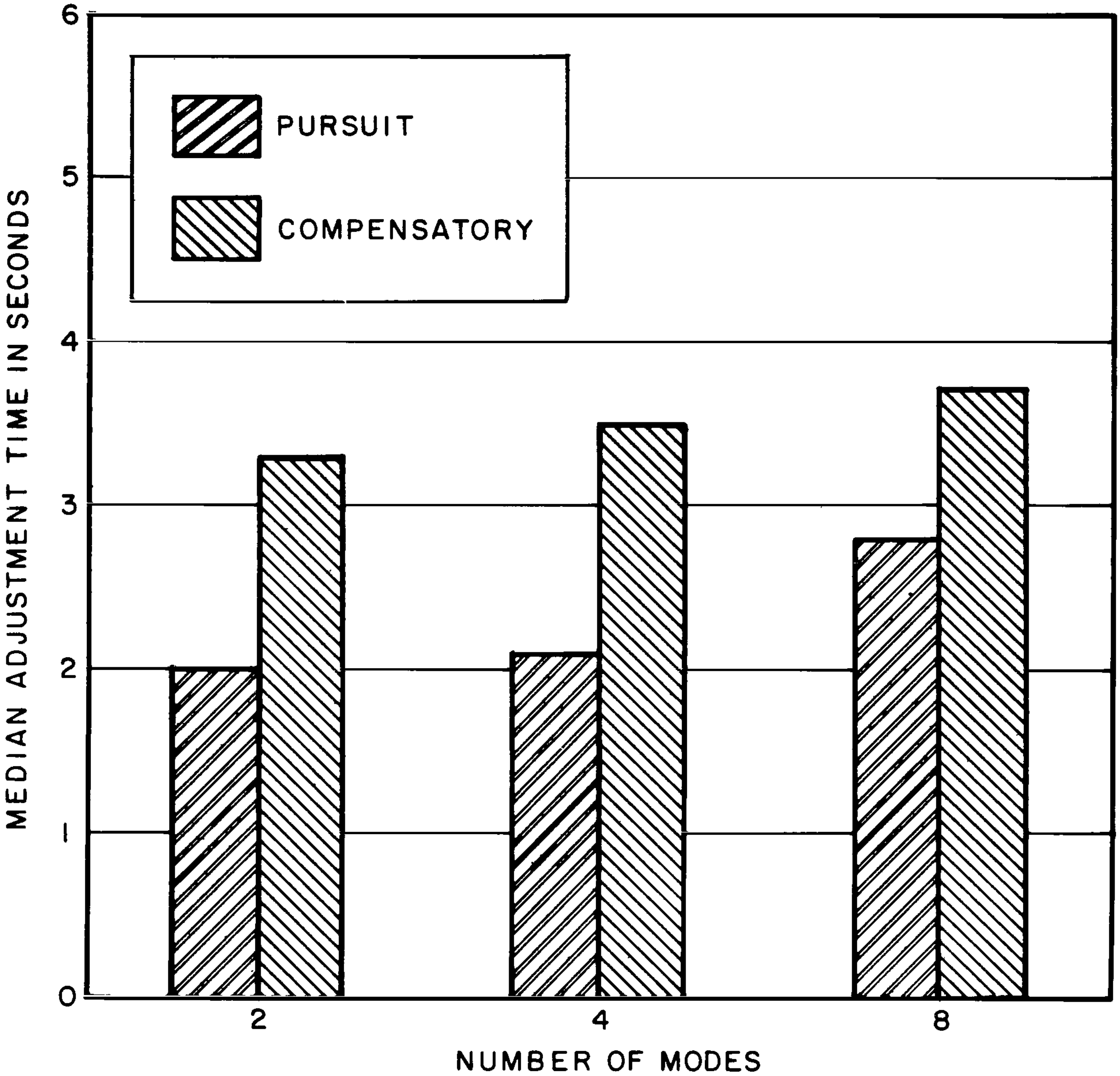

FIG. 3 MEDIAN ADJUSTMENT TIMES BY NUMBER OF MODES AND DISPLAY MODALITY

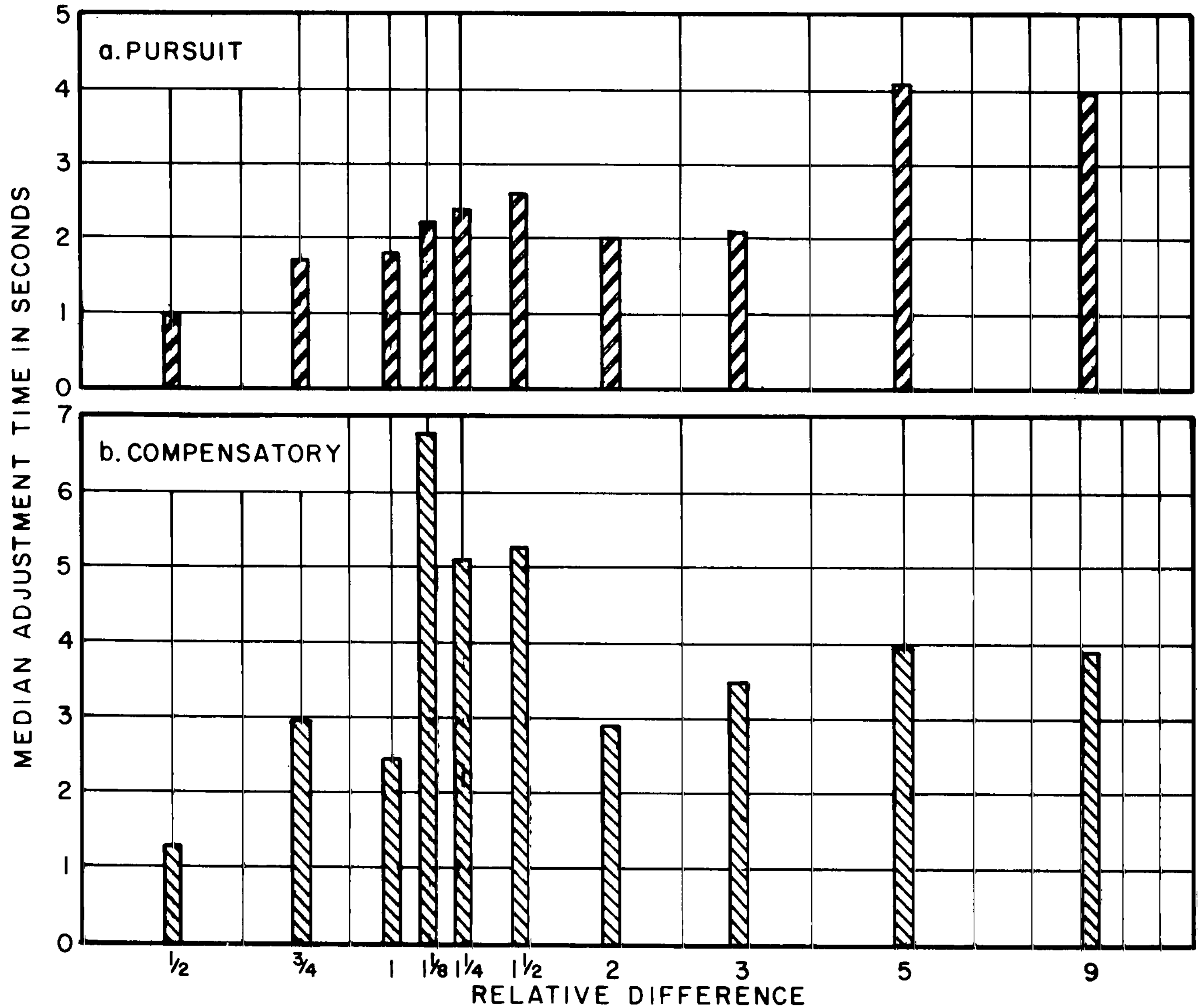

FIG. 4 MEDIAN ADJUSTMENT TIMES BY RELATIVE DIFFERENCE OF THE TRANSITION

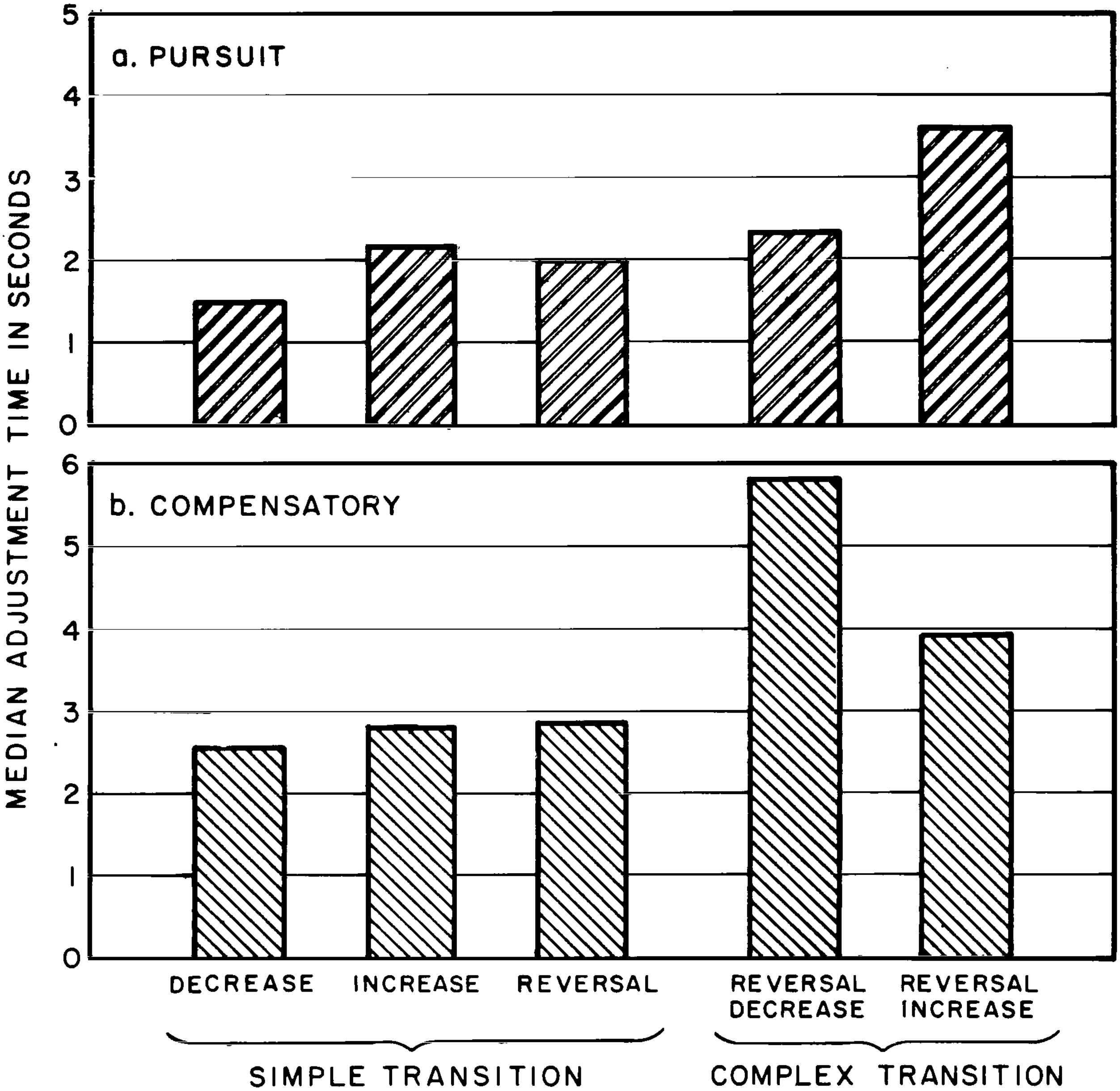

FIG.5 MEDIAN ADJUSTMENT TIMES BY TYPE AND COMPLEXITY OF TRANSITION

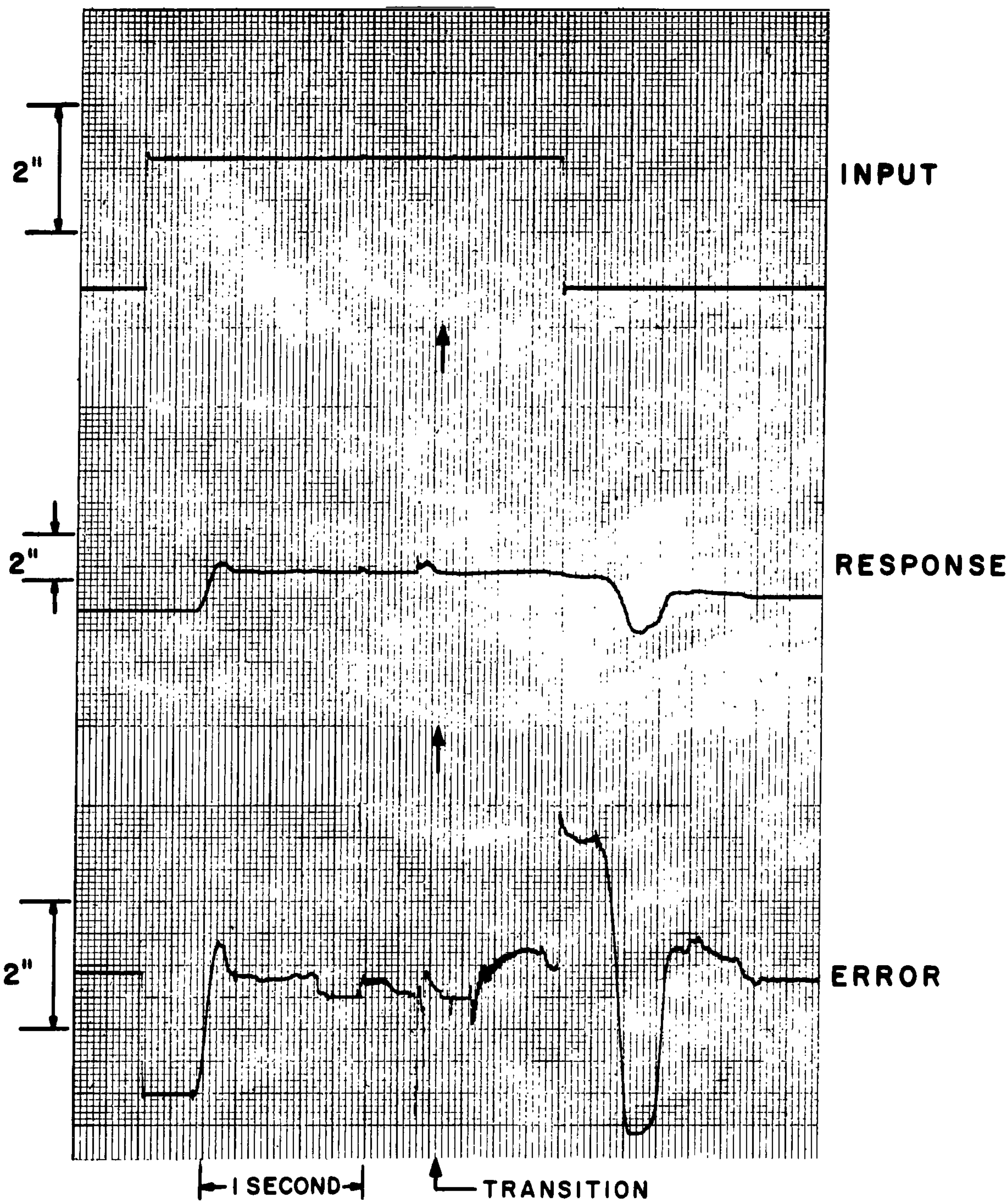

FIG.6 STEP RESPONSE BEFORE AND AFTER A GAIN INCREASE
SUBJECT LRY, +6 → +11

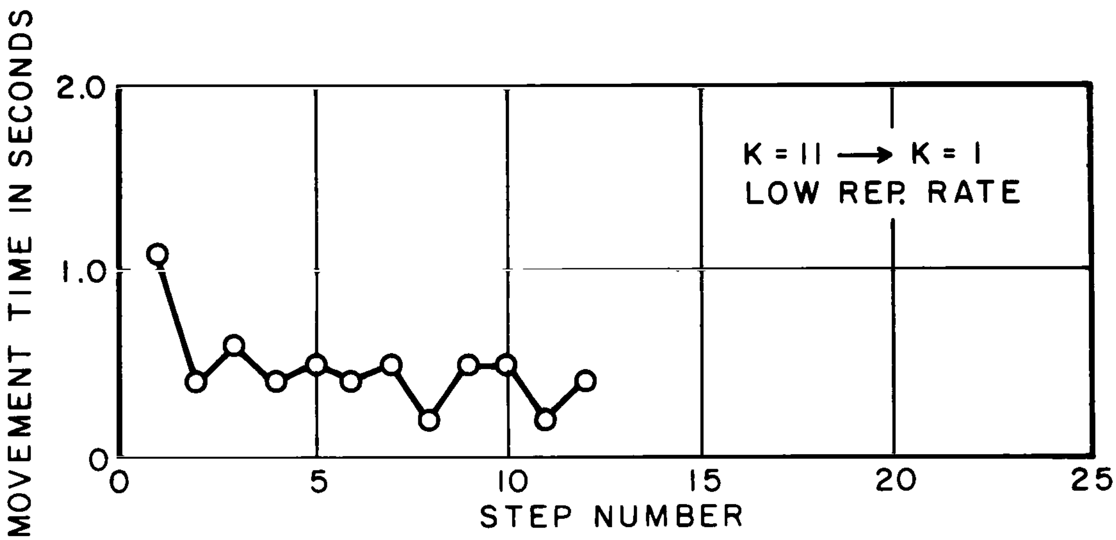

FIG. 7 ADAPTATION TO RANDOM STEPS AFTER TRAINING

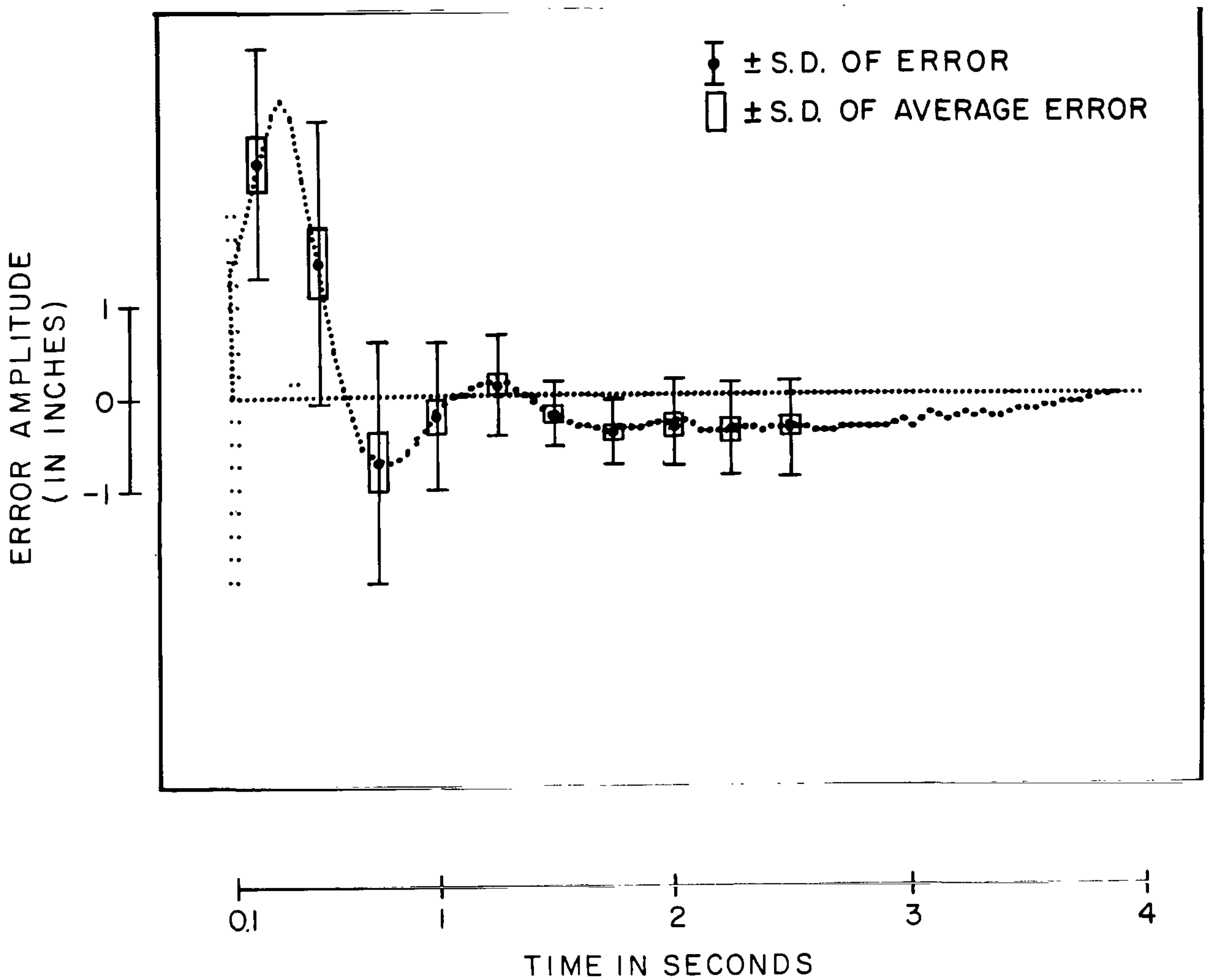

FIG.8 AVERAGE ERROR WAVEFORM FOLLOWING A +2 → −8 TRANSITION SHOWING STANDARD DEVIATION OF ORIGINAL ERROR DISTRIBUTION AND OF AVERAGE ERROR

SUBJECT RB

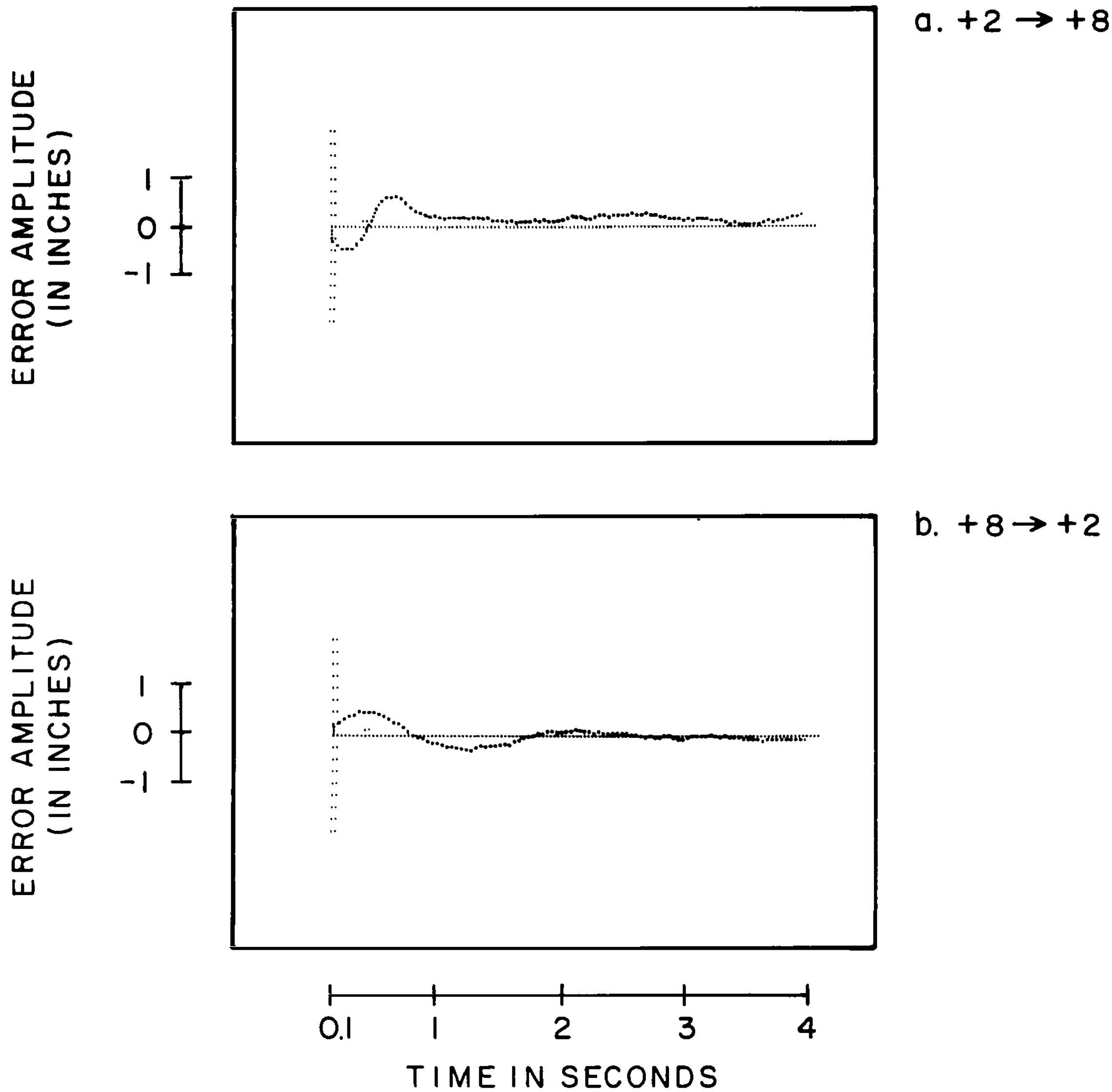

FIG. 9 AVERAGE ERROR WAVEFORMS WITH DIFFERENT TYPES OF TRANSITION
SUBJECT LRY, 2 MODES, PURSUIT, (R·64)

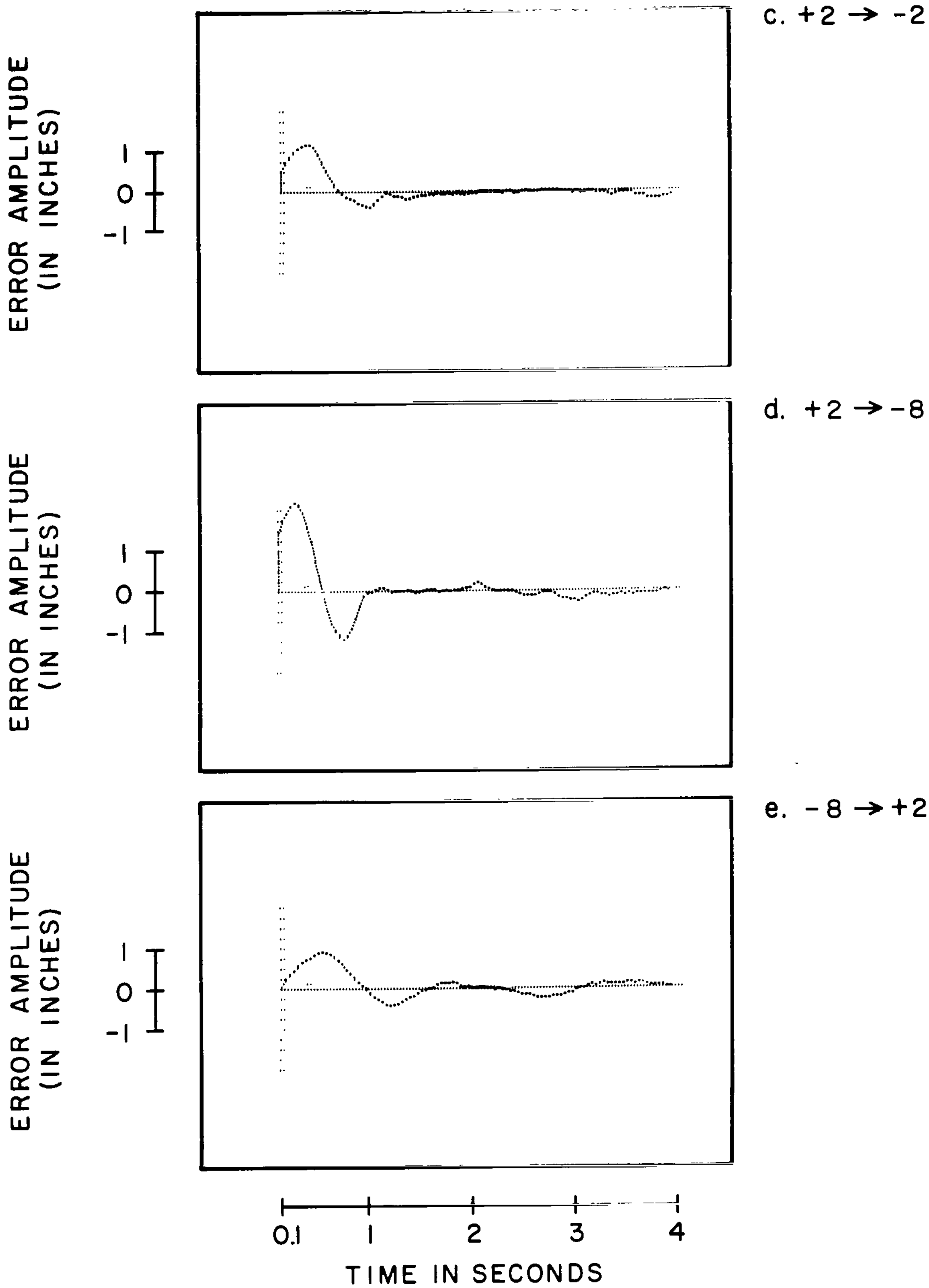

FIG.9 CONTINUED
SUBJECT LRY, 2 MODES, PURSUIT, (R·64)

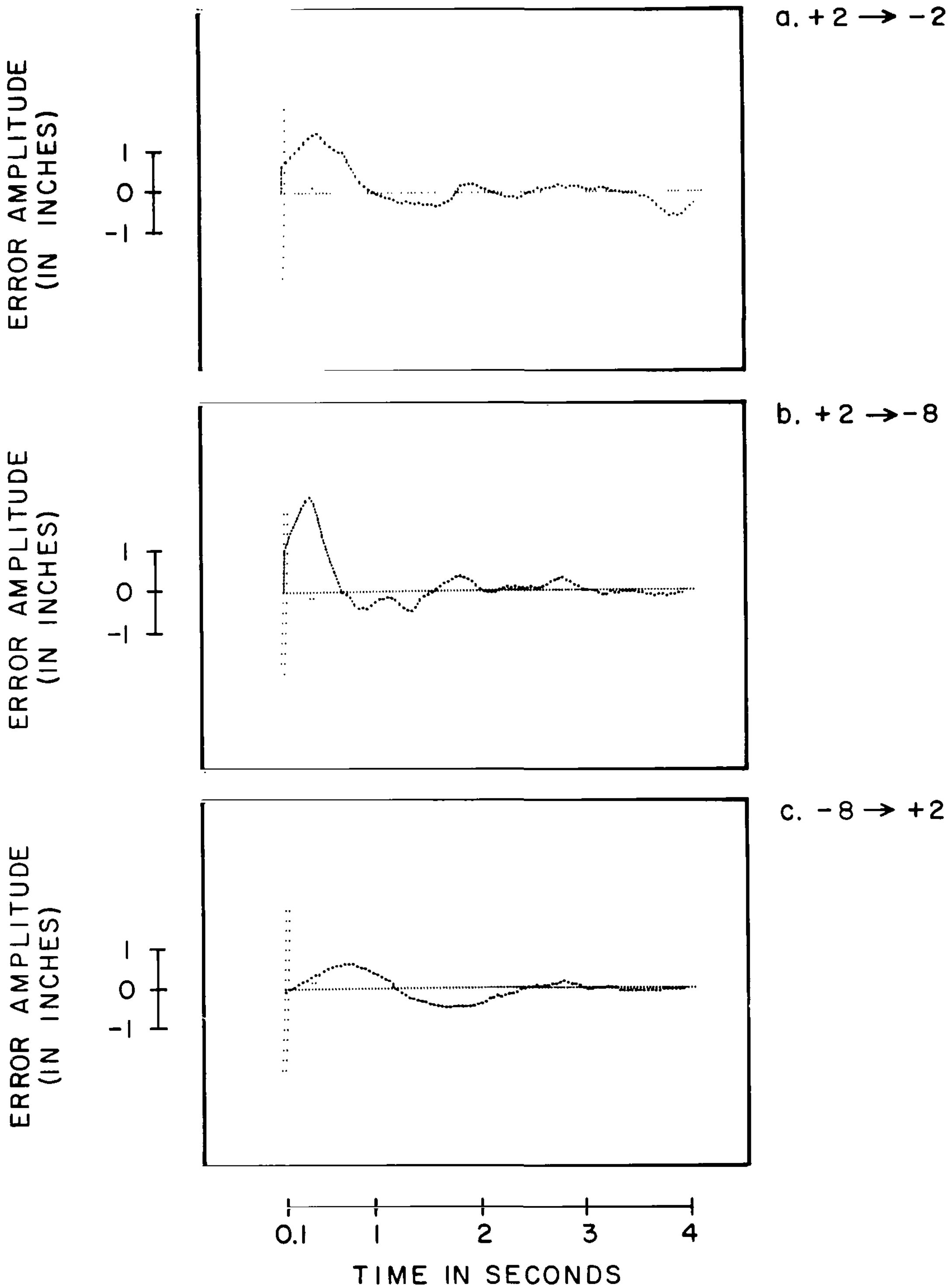

FIG.10 AVERAGE ERROR WAVEFORM WITH DIFFERENT TYPES OF TRANSITION
SUBJECT LRY, 2 MODES, COMPENSATORY, (R·64)

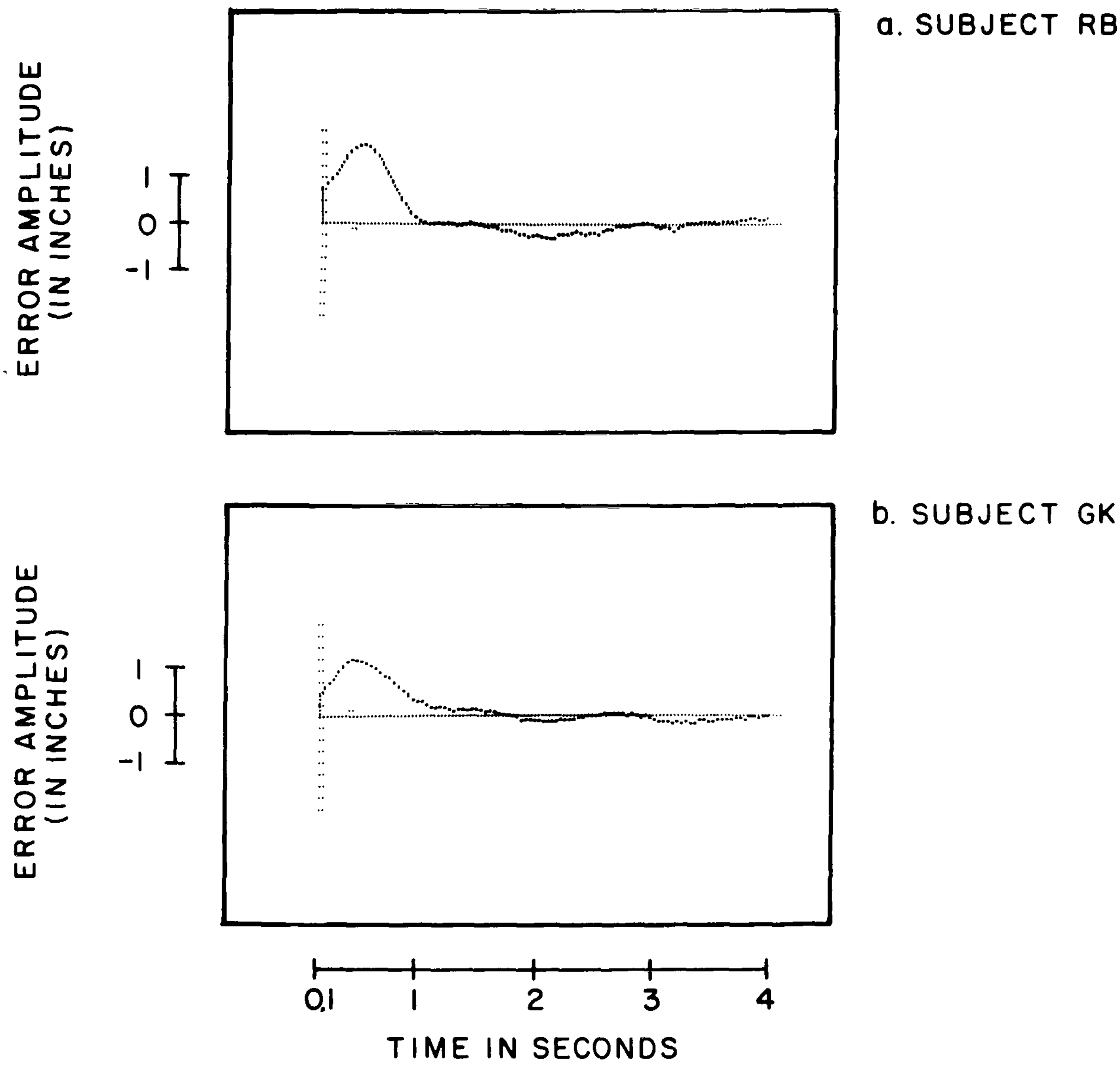

FIG.11 AVERAGE ERROR WAVEFORM WITH POLARITY REVERSAL
2 MODES, COMPENSATORY, (R·24), +2 → -2

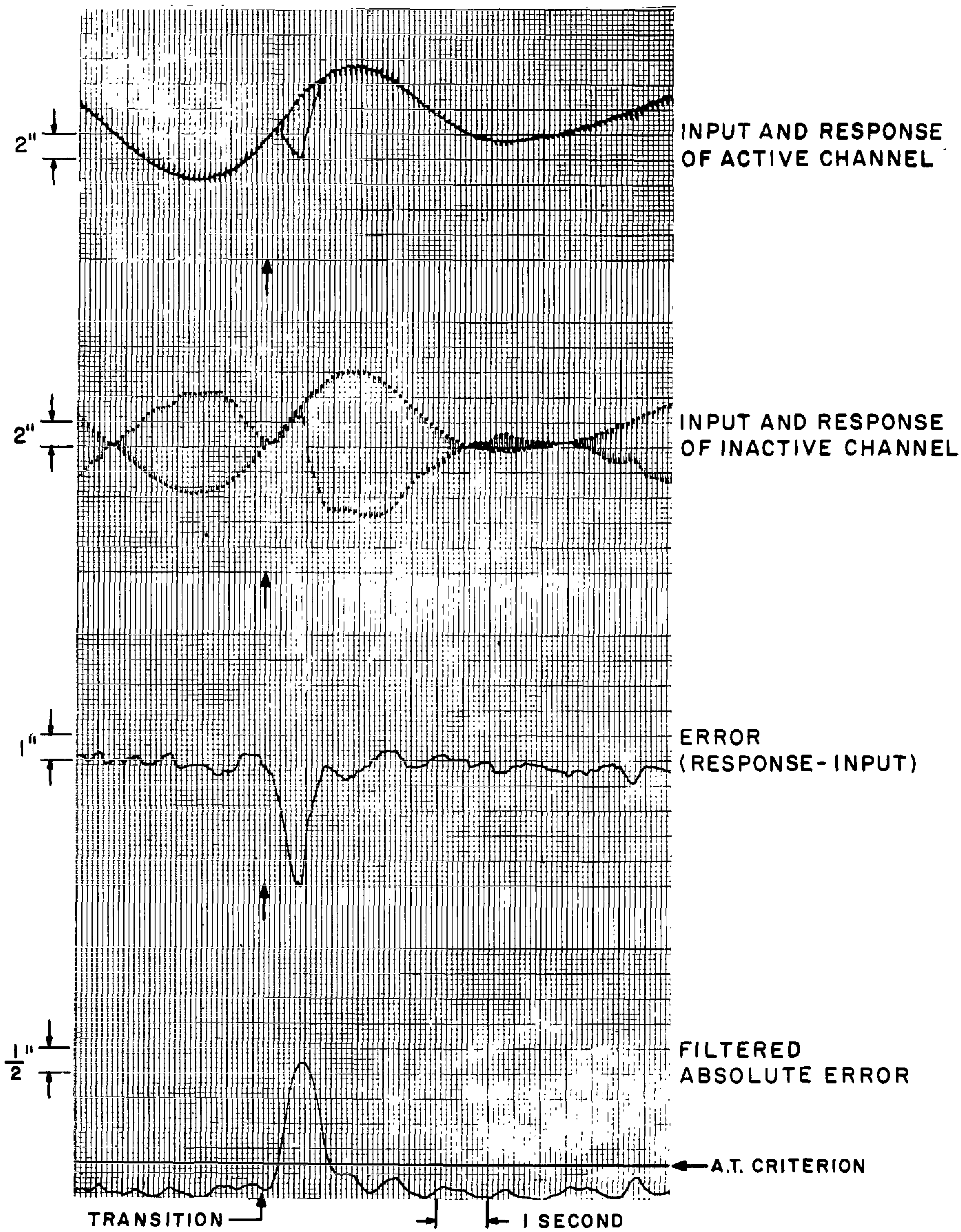

FIG.12 TIME TRACING WITH POLARITY REVERSAL
SUBJECT RB, 2 MODES, COMPENSATORY, (R·24), +2 → −2

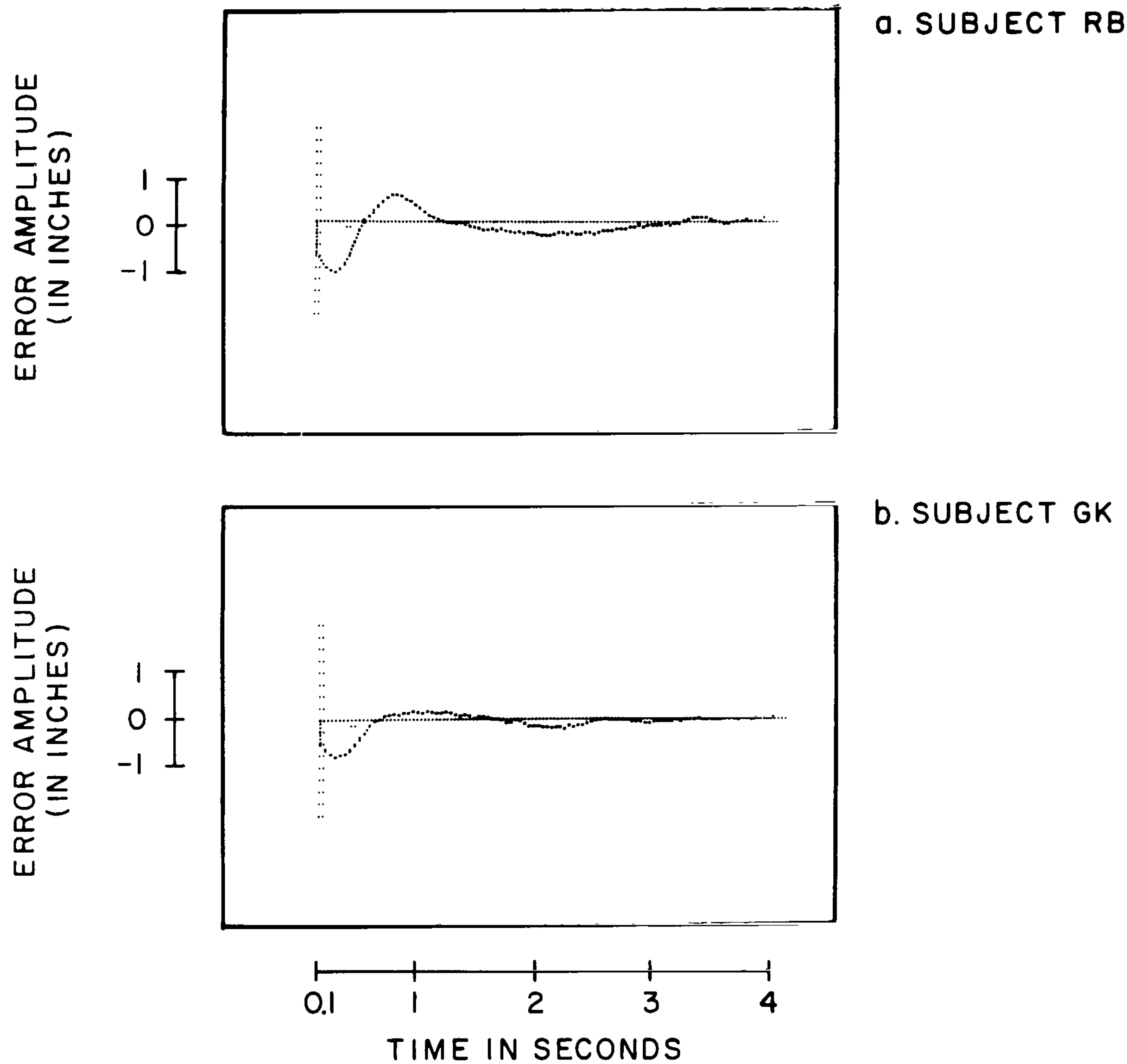

FIG.13 AVERAGE ERROR WAVEFORM WITH GAIN INCREASE
2 MODES, COMPENSATORY, (R·24), +2 ⟶ +8

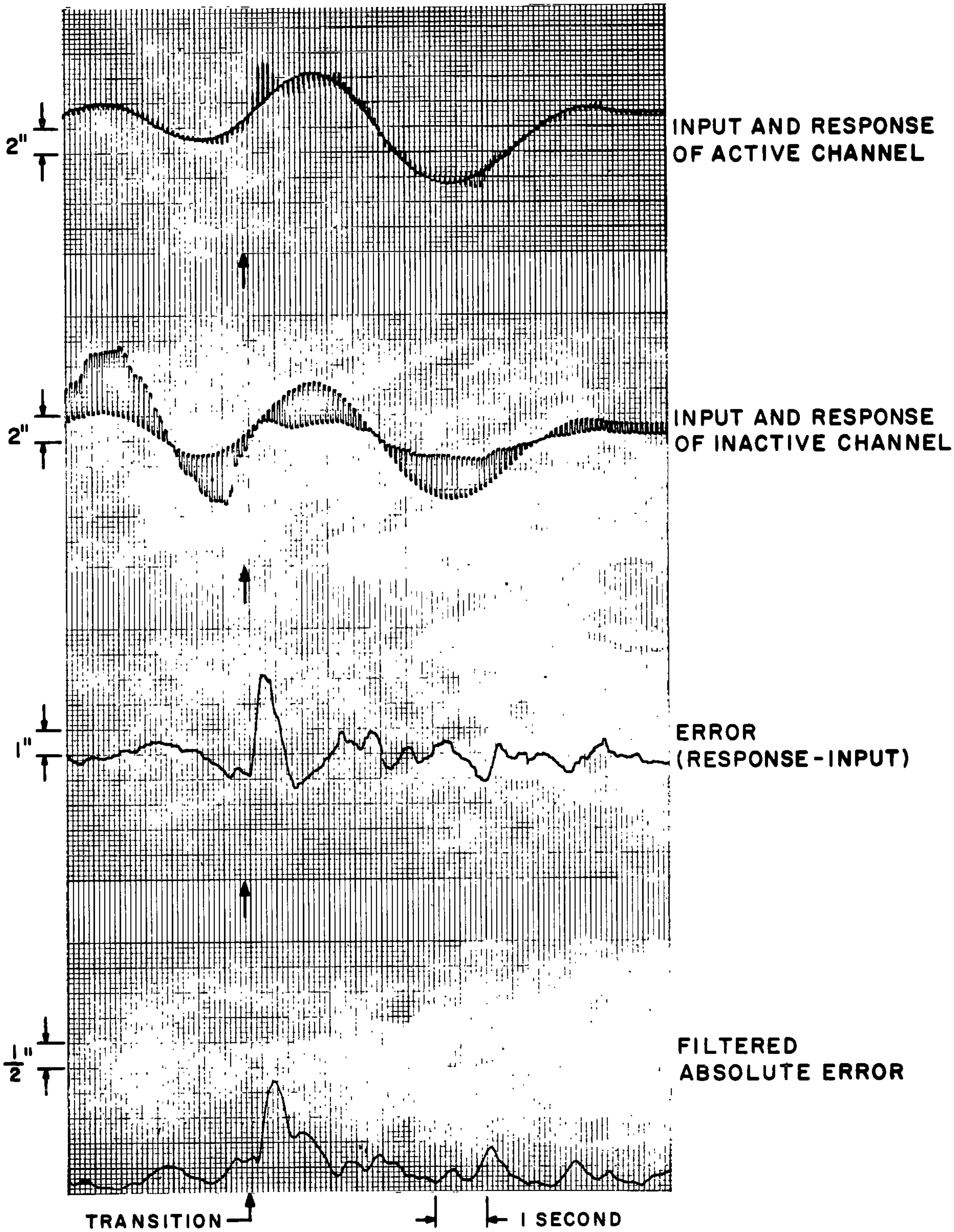

FIG.14 TIME TRACING WITH GAIN INCREASE
SUBJECT RB, 2 MODES, COMPENSATORY, (R · 24), +2 → +8

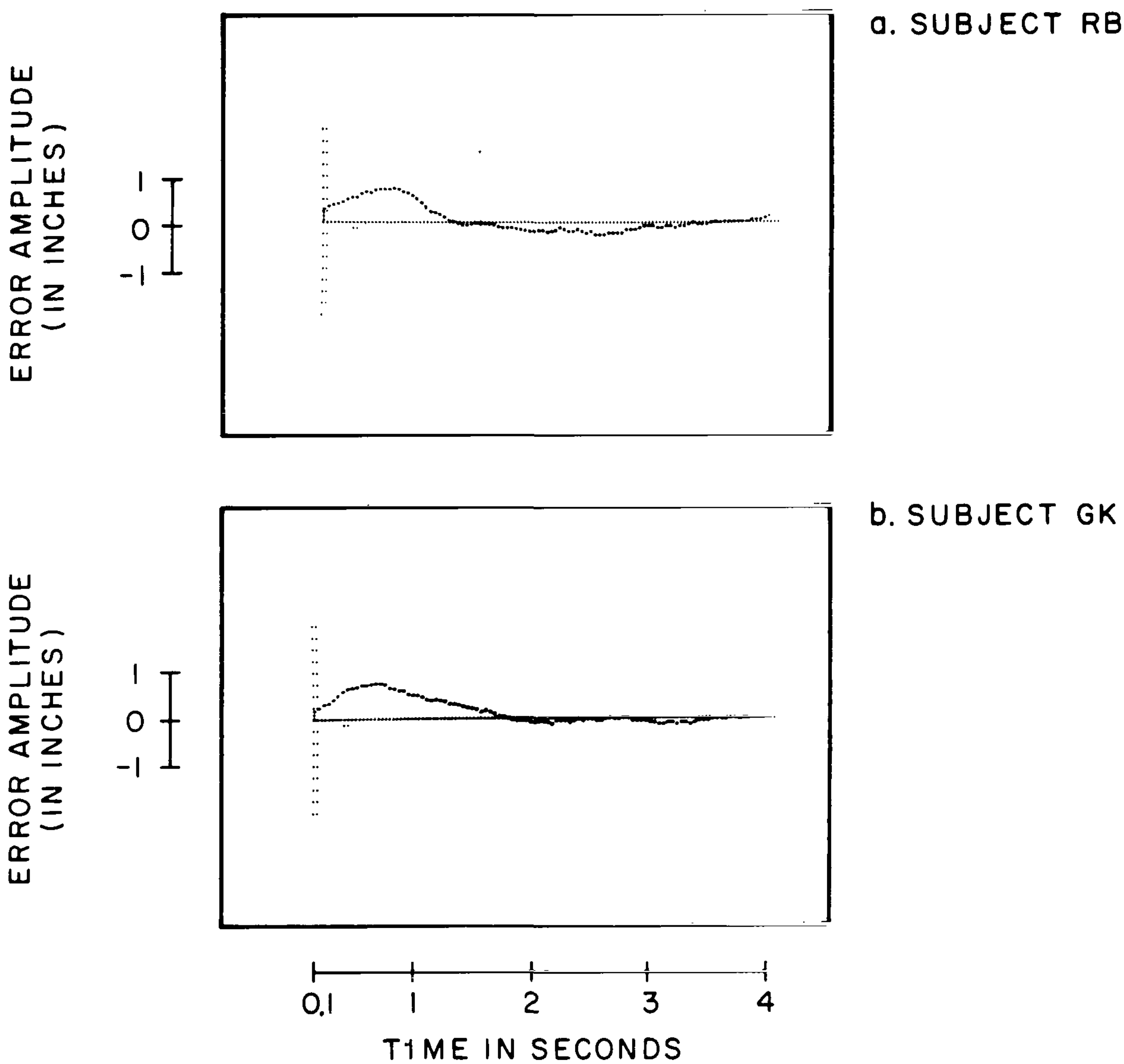

FIG.15 AVERAGE ERROR WAVEFORM WITH GAIN DECREASE
2 MODES, COMPENSATORY, (R·24), +8 → +2

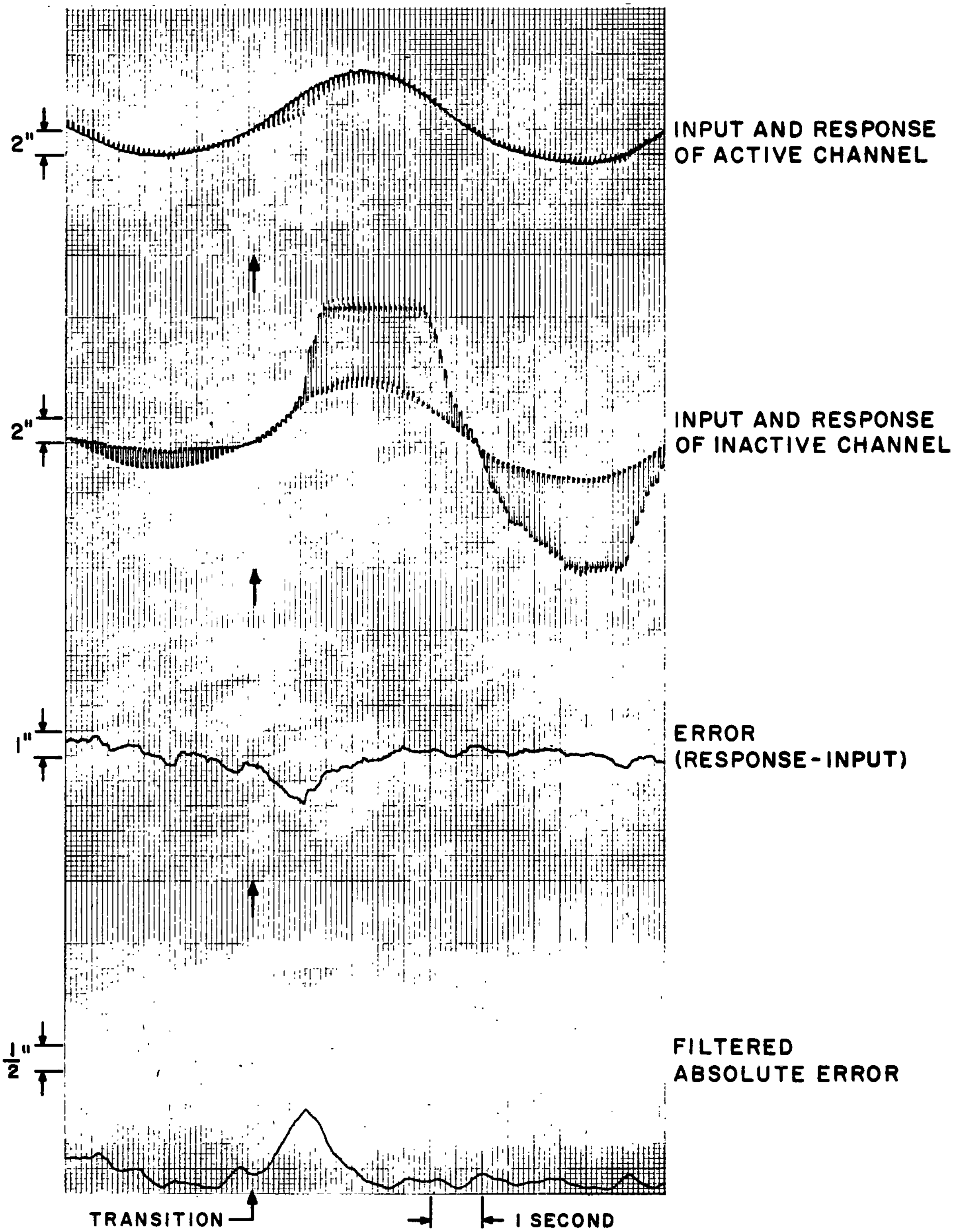

FIG. 16 TIME TRACING WITH GAIN DECREASE

SUBJECT RB, 2 MODES, COMPENSATORY, (R · 24), +8 → +2

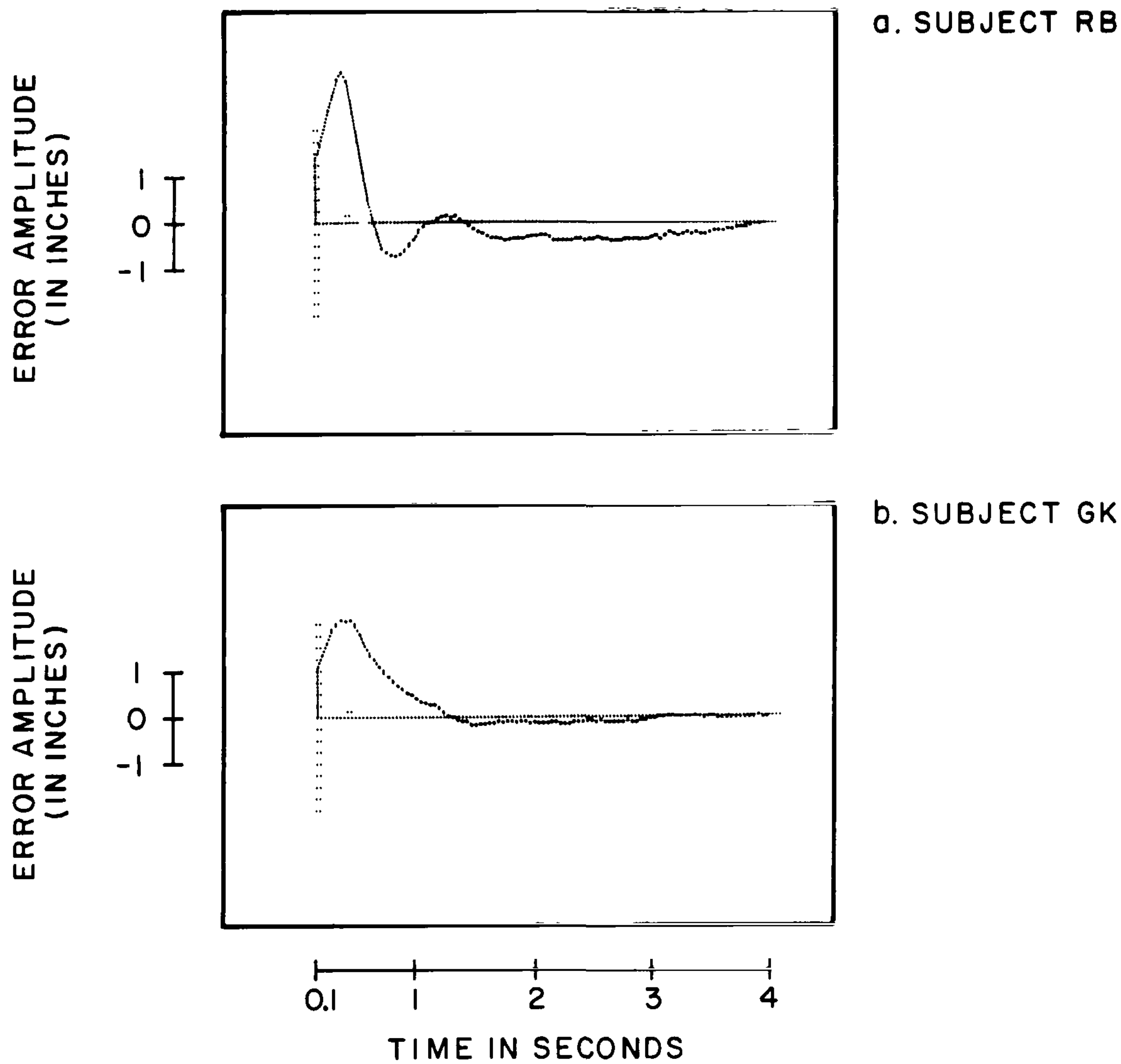

FIG. 17 AVERAGE ERROR WAVEFORM WITH POLARITY REVERSAL AND GAIN INCREASE

2 MODES, COMPENSATORY, (R·24), +2 → -8

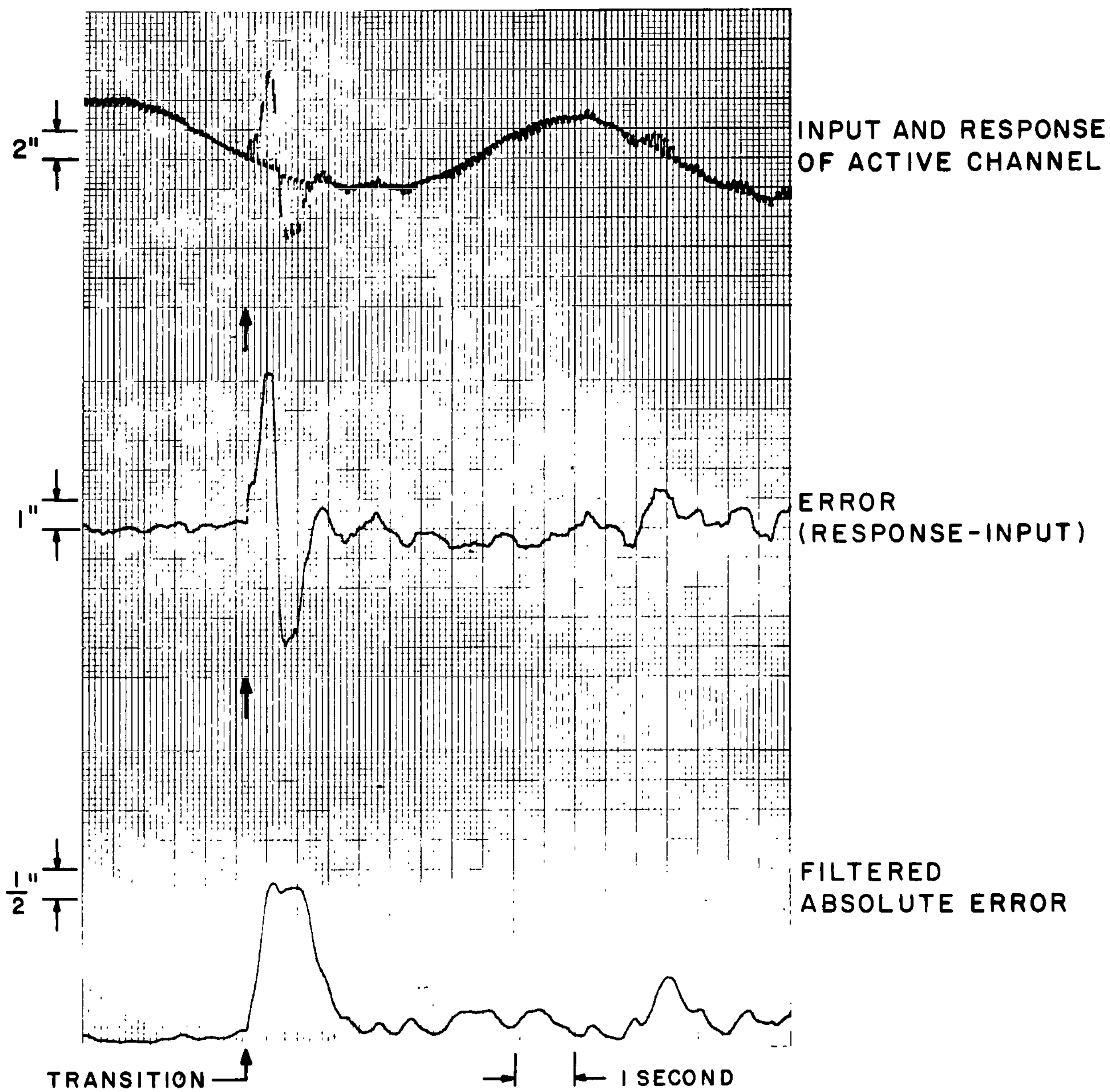

FIG.18 TIME TRACING WITH POLARITY REVERSAL AND GAIN INCREASE

SUBJECT RB, 2 MODES, COMPENSATORY, (R·24), + 2 → -8

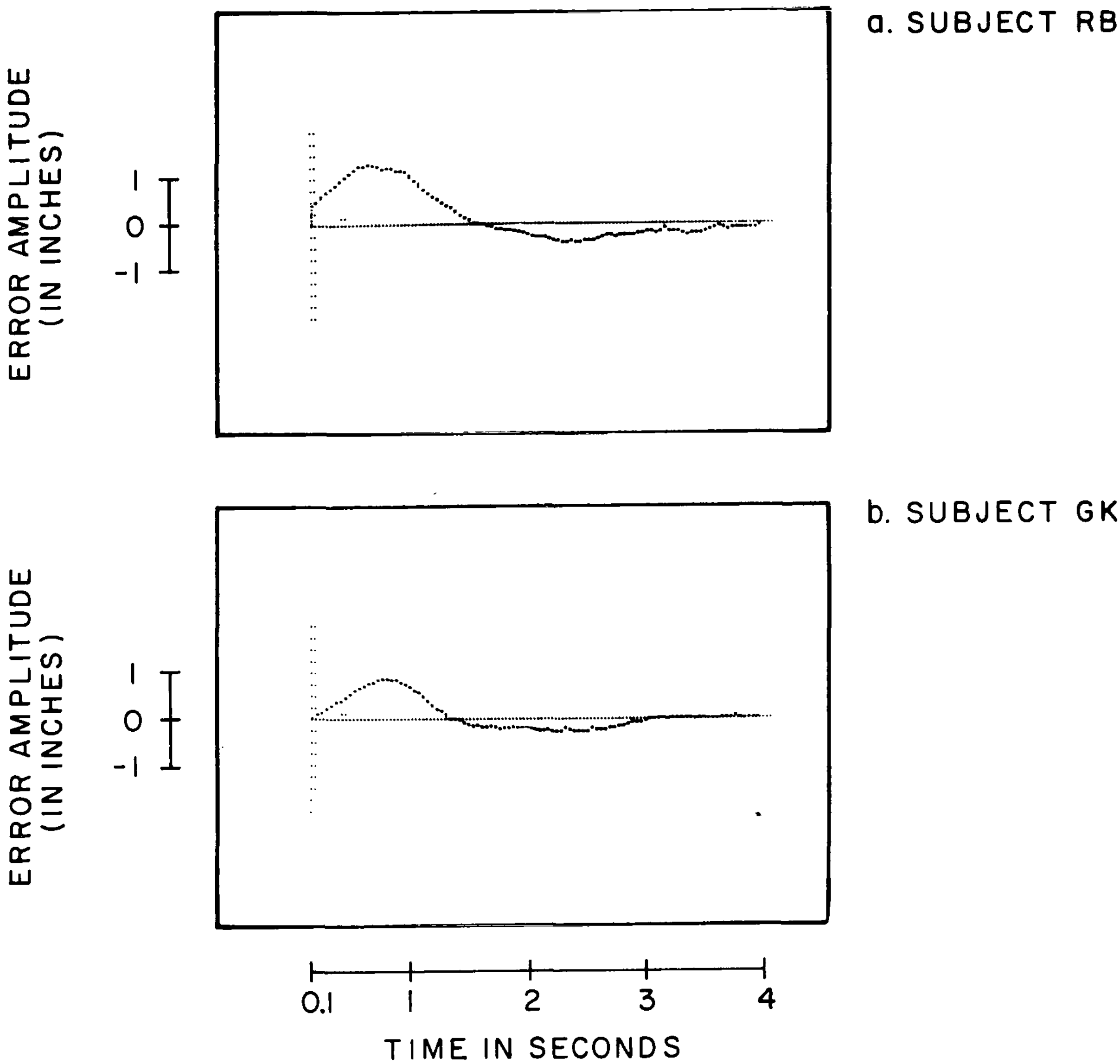

FIG.19 AVERAGE ERROR WAVEFORM WITH POLARITY REVERSAL AND GAIN DECREASE
2 MODES, COMPENSATORY, (R·24), -8 → +2

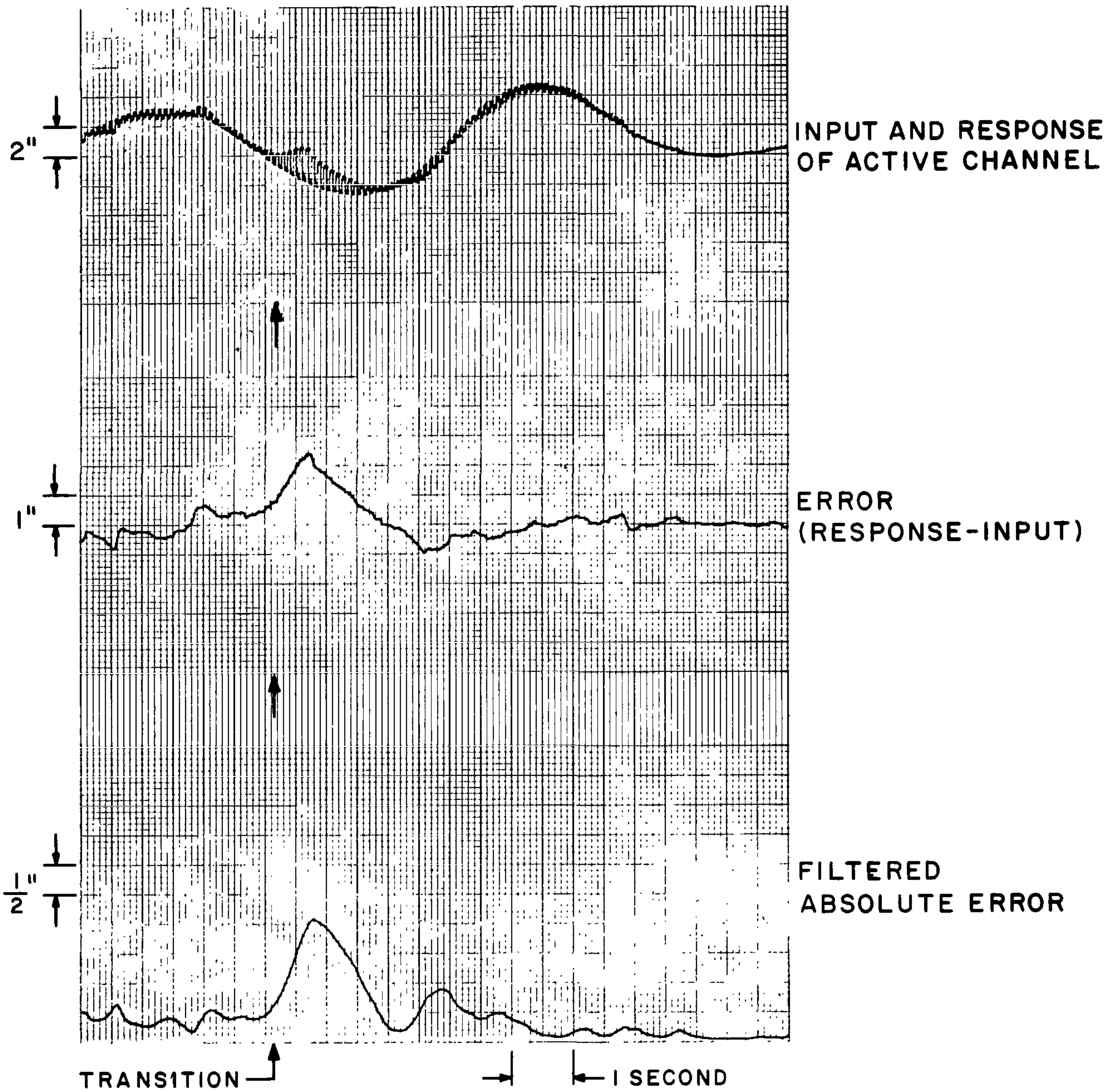

FIG. 20 TIME TRACING WITH POLARITY REVERSAL AND GAIN DECREASE

SUBJECT RB, 2 MODES, COMPENSATORY, (R · 24), −8 → +2

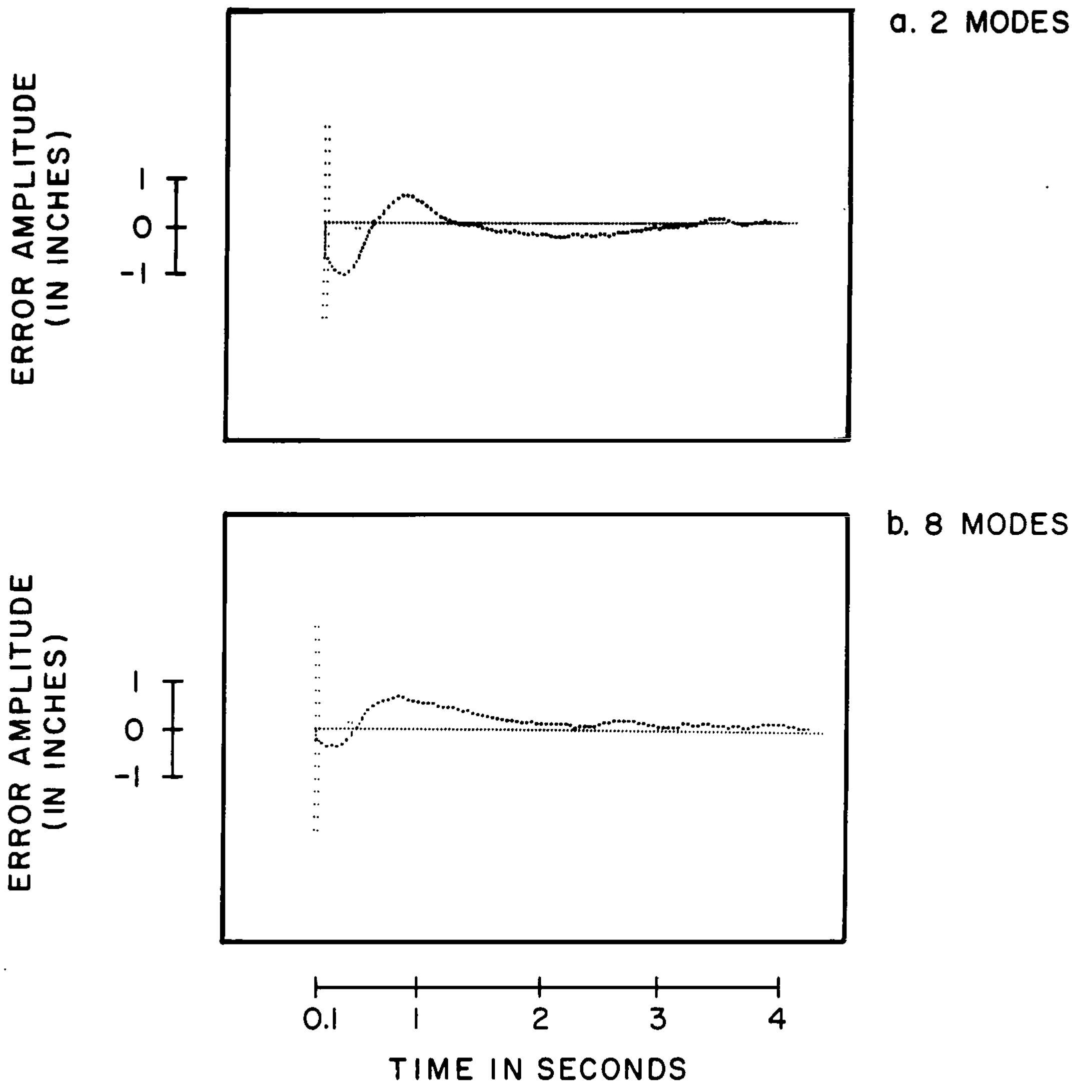

FIG.21 AVERAGE ERROR WAVEFORM COMPARING 2 AND 8 MODES
SUBJECT RB, COMPENSATORY, (R·24),+2→ +8

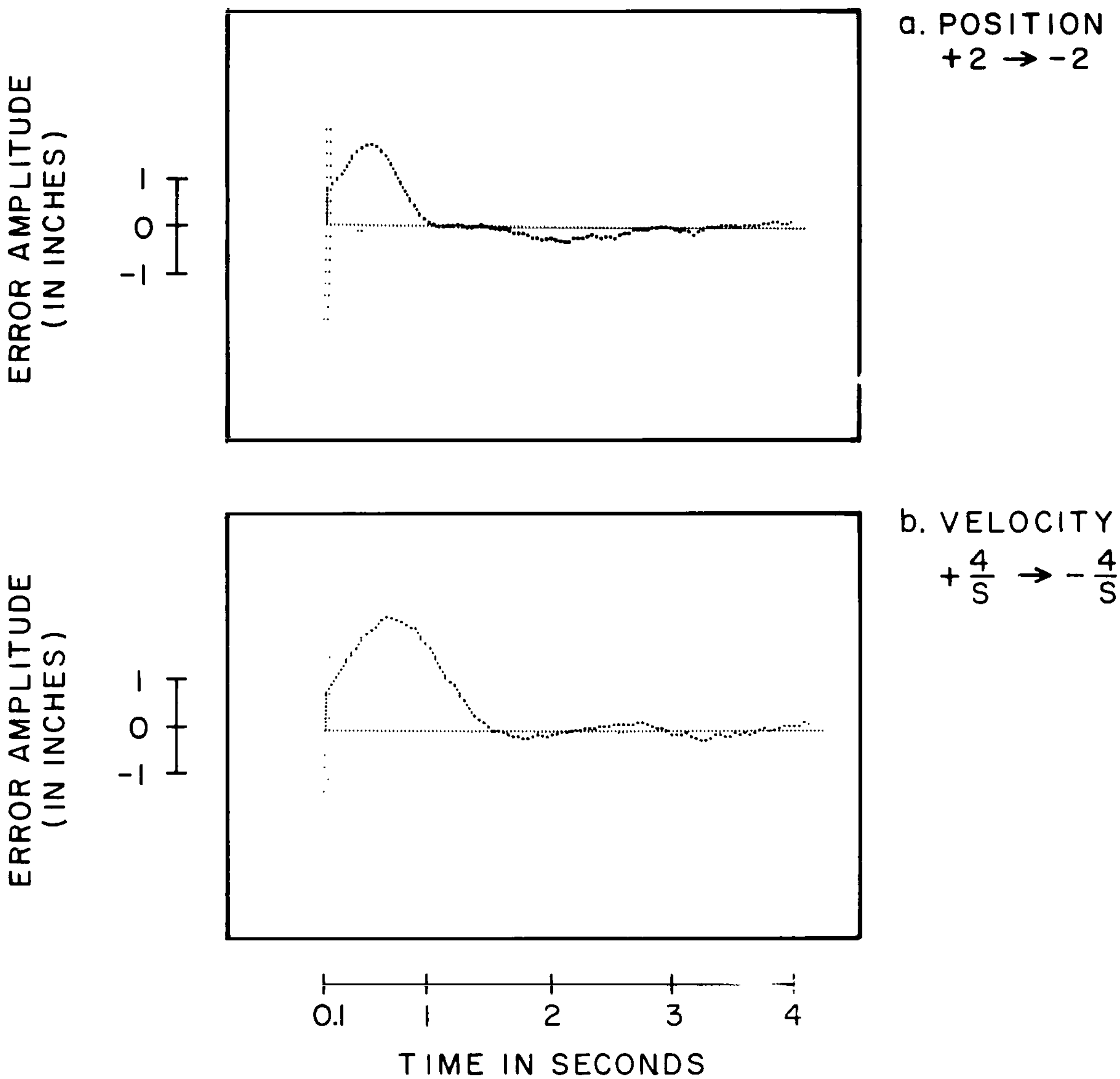

FIG. 22 AVERAGE ERROR WAVEFORM FOR VELOCITY CONTROL COMPARED WITH POSITION CONTROL
SUBJECT RB, 2 MODES, COMPENSATORY, (R·24)

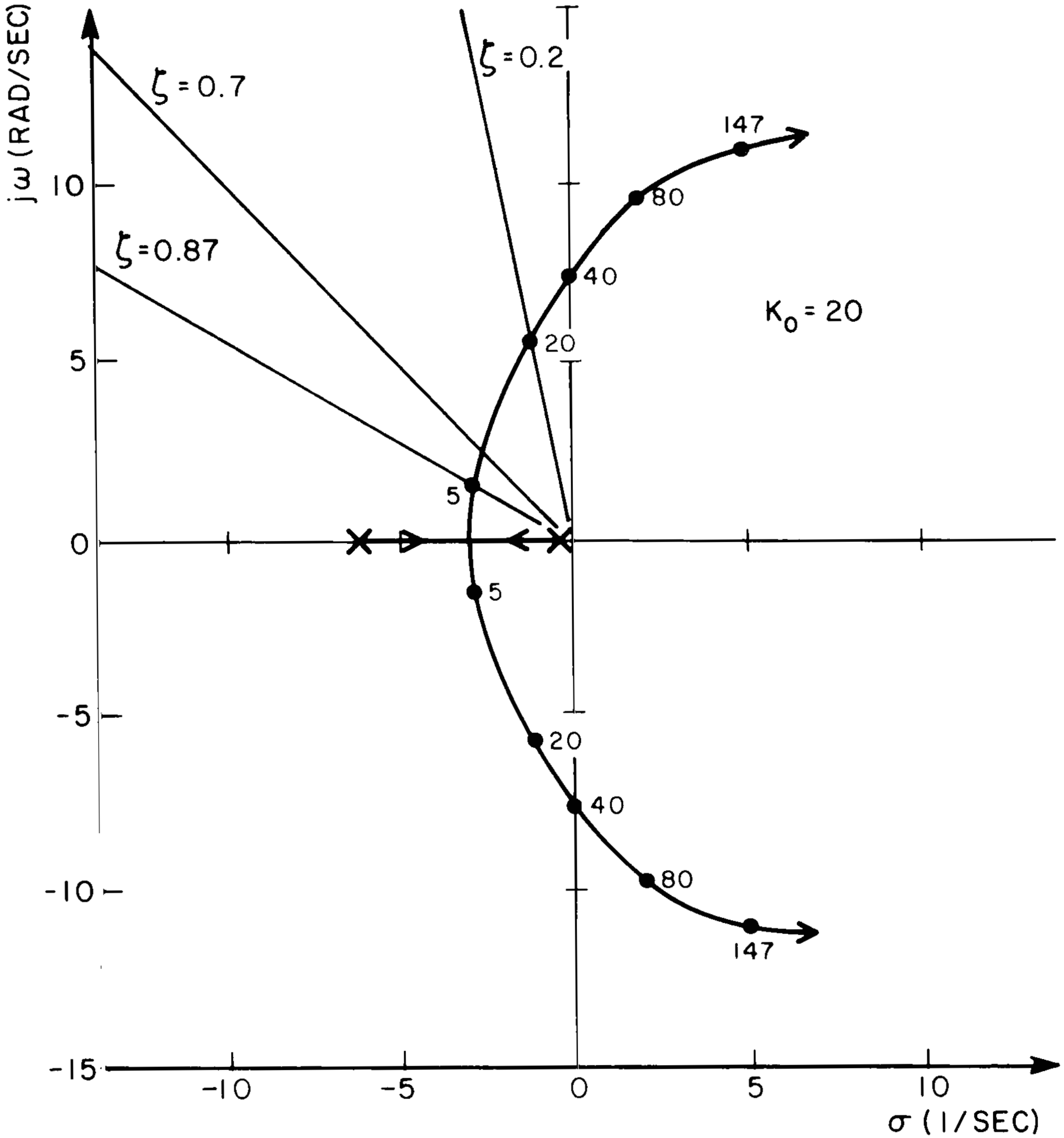

FIG. 23 HUMAN OPERATOR CLOSED-LOOP ROOT LOCUS FOR POSITIVE K FROM ELKIND'S DATA R·24 (Y_c=1)

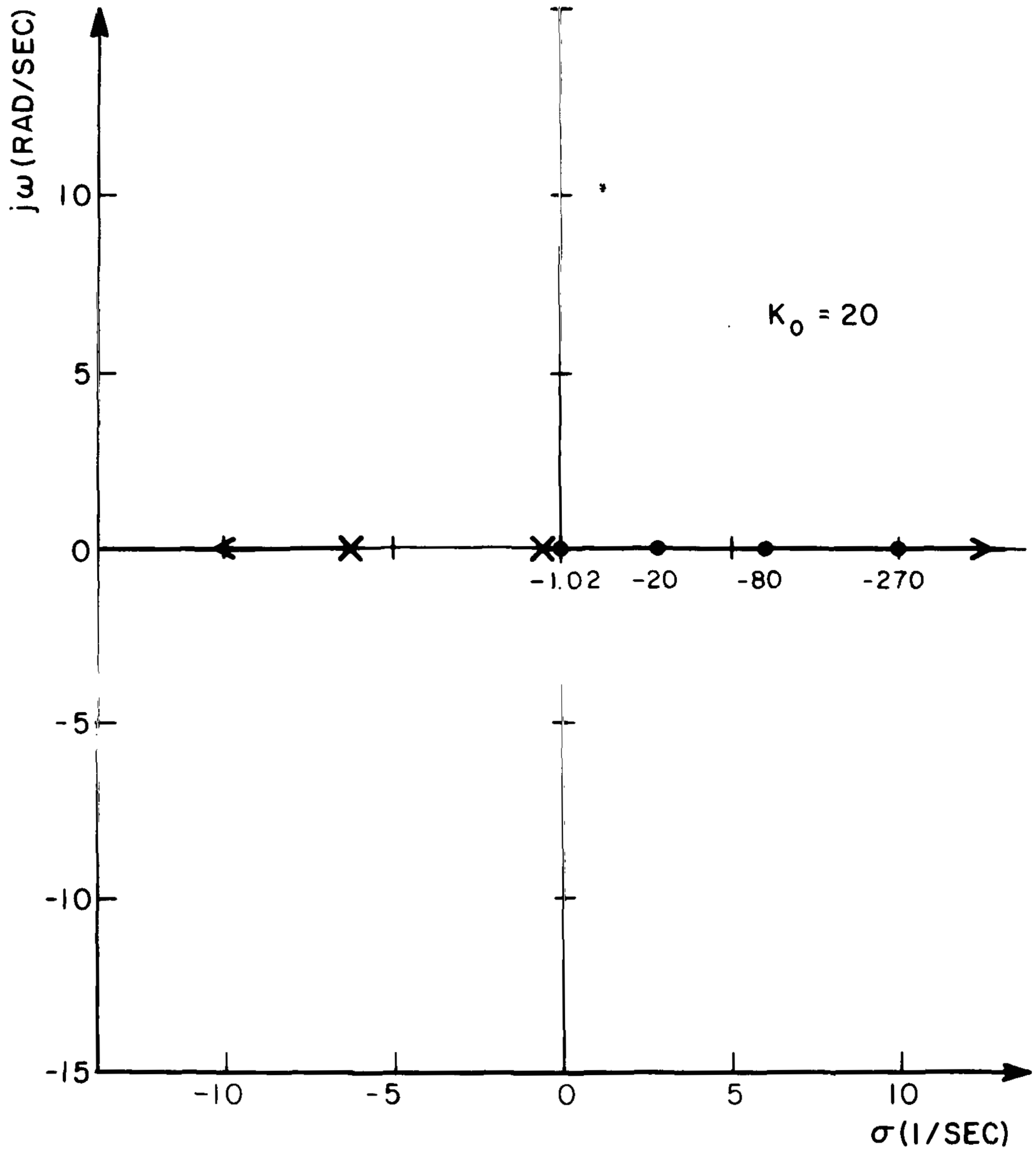

FIG.24 HUMAN OPERATOR CLOSED-LOOP ROOT LOCUS FOR NEGATIVE K
($Y_c = 1$)

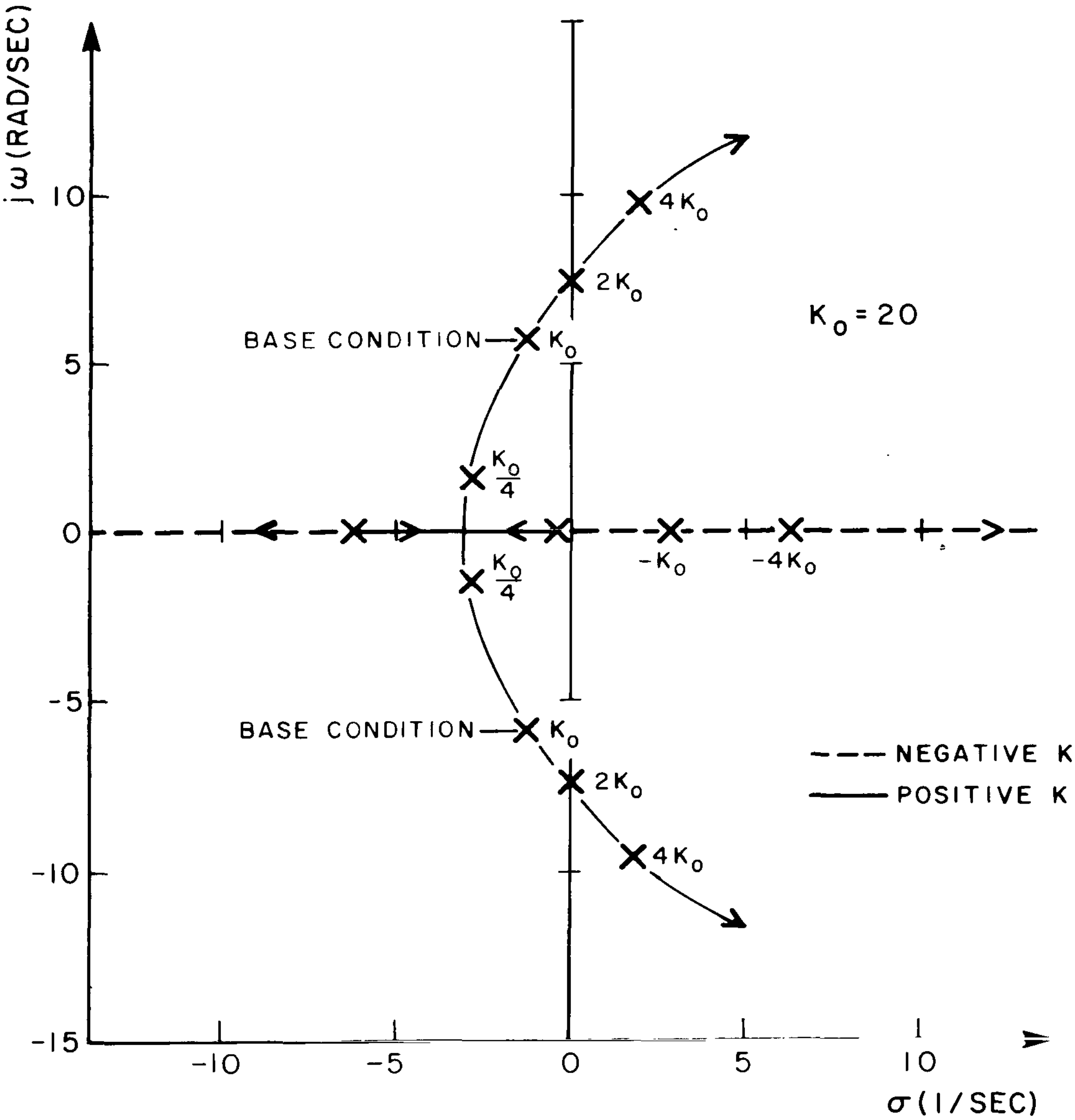

FIG. 25 POLE POSITIONS FOR OTHER THAN NORMAL GAIN

APPENDIX A

ANALOG COMPUTER BLOCK DIAGRAMS

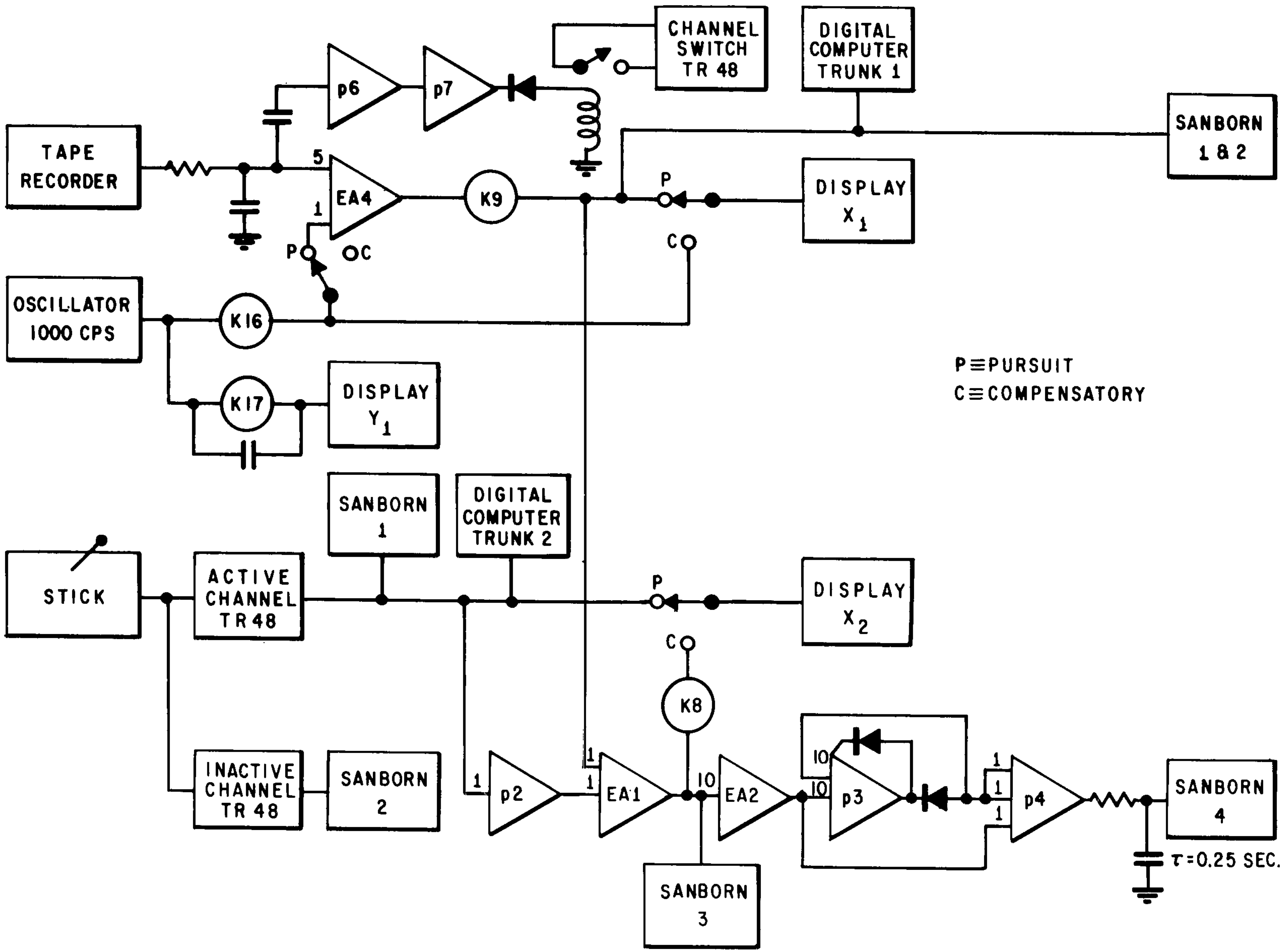

FIG.A-1 ANALOG COMPUTER PROGRAM - EA

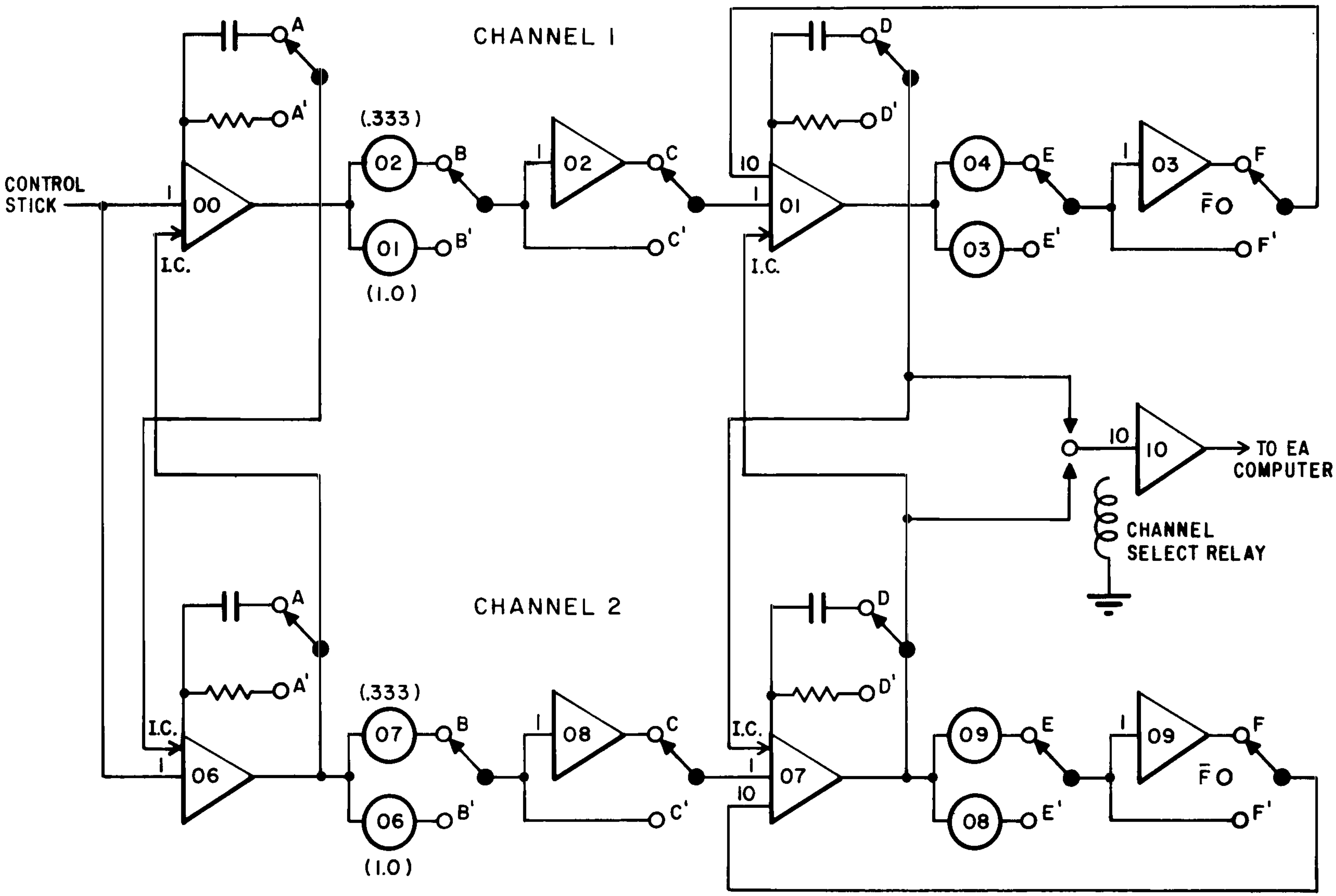

FIG.A-2 TR-48 PROGRAM FOR MANY CONTROL MODES

APPENDIX B

EXPERIMENTAL PROCEDURE

The experiments conducted in this investigation fall into three major categories. The adjustment time experiments measured the time for subjects to reduce their tracking error following a controlled element transition with a random continuous input. In the average error computation experiments the waveform of error following many controlled element transitions of a particular type were averaged to reveal consistencies in the adaptation process. Finally, in the step experiments, subject performance following a controlled element transition was observed for the case of random step input signals.

B.1 Adjustment Time Experiment

Pursuit and compensatory tracking were investigated to determine the effect of sudden changes in controlled element gain or polarity on the closed-loop performance including the human operator. The input signal was a sum of more than forty sinusoids, approximating low-frequency Gaussian noise. It had a rectangular spectrum of high-frequency cutoff at 0.64 cps (Elkind's R.64 Spectrum) and RMS amplitude of 1.5 inches on the display screen - providing a reasonably challenging tracking task.[7]

Subjects. The subjects used for this experiment were five male undergraduate students. They were selected on the basis of their performance in a preliminary session from an original group of eight. The five best subjects in this session were all engineering students. All were drivers, and one (S3) had some limited experience as a pilot.

Conditions. All subjects tracked under 8 gain conditions, with both pursuit and compensatory displays, and sessions in which either 2, 4 or 8 different gains were involved. The gains were +1, +2, +4, +8, -1, -2, -4, -8, where a gain of +1 corresponds to a $\pm 6''$ deflection of the controlled dot (that is, full scale) for the full $\pm 45^{\circ}$ deflection of the control stick.

Out of the total of 56 different transitions possible among the 8 modes, a basic set of 24 was chosen. These covered the range from easy to difficult to detect, defined on the basis of relative differences (see Section III). These 24, which were in fact 12 pairs (e. g. +1 to -8 and -8 to +1) were used in all the conditions investigated.

In the "2 mode" conditions the subjects were given only 2 gain conditions, and were given a practice on each before the beginning of the run. In the "4 mode" conditions 4 of the 8 gains were involved, and the subjects were again given a familiarization period on each. Three such sets of 4 modes were used, and the subjects were given transitions of each of the 12 types in each set. Besides the 24 basic transitions, these sets involved another 10, and the repetition of 2 of the original 24. In the "8 mode" conditions all 8 gains could occur. They were arranged so that only the 34 types of transition used in the 4 mode conditions were involved.

Instructions. Before the first practice session the subjects were given basic instructions for the pursuit condition. These were as follows:

"You will be seated in a small cubicle with a control stick mounted on a right arm rest. In front of you there will be a television-type screen, covered with a mask except for the center section. When the signal is switched on you will see a circle of light which will move across the screen. It will always stay in the same horizontal line, but the distance and speed it will move will vary. You will also see a spot of light on the screen in the same horizontal line. You can control the position of that with your control stick, and your task is to keep the spot as near as possible to the center of the circle.

"That is the basic task, but the relationship between what you do with the control stick and what happens to the spot as a result of your action will not always be the same. There are going to be 8 different "gain" conditions. I'll explain what I mean. For a gain of +1, if you move the stick one unit to the right the spot will move one unit to the right. For gains of +2, +4, and +8 a stick movement of one unit will produce a spot movement of 2, 4, and 8 units respectively. The other 4 conditions are the reverse of these. A gain of -1 means that a stick movement of one unit right will produce a spot movement of one unit left, and for -2, -4 and -8 gains a movement of one unit right will produce a spot movement of 2, 4 and 8 units left respectively. Today you will be given practice in tracking under these 8 conditions."

The second time the subjects came they were given practice in transitions, and the instructions were supplemented as follows:

"Instead of always knowing at the beginning of the run what gain condition you will be tracking with, today the conditions will change during the run. You will not be given any warning of when these changes will occur, but at the beginning of each run you will be told how many different gains will occur in that run, and will have a chance to practice on each. Sometimes there will only be two different gains in a run, sometimes 4 and sometimes all 8. Transitions between gains will always occur when the spot is passing through the central point of the screen.

"When transitions occur you should try to adapt to the new conditions as quickly as possible."

Design. All subjects began with practice sessions on pursuit tracking under all 8 gain conditions, and then practice with transitions. By the time the experimental runs were started they were all well practiced in the pursuit conditions, having had a minimum of 1-1/2 hours of training over two or three sessions.

There were in all 12 sessions for each subject in the experiment excluding practice runs. They consisted of 2 sessions each of 2, 4 and 8 modes under pursuit and compensatory conditions. A session involved all the different transitions possible under that condition, each occurring once, except that for the 2 mode conditions a session consisted of each of the two transitions occurring twice.

Each session was divided into 3 blocks. For the 2 mode conditions a block consisted of one pair of transitions - practice on each, followed by 2 transitions in each direction. Immediately following this they were shown a second pair of modes, treated in the same way. There were, then, 2 pairs of gains in each block, and the blocks were separated by 2 minutes rest. There were 6 pairs in a session.

For the 4 mode conditions a block consisted of the practice and the 12 possible transitions for a set of 4 modes arranged in a random order. Again 2 minutes rest separated each of the 3 blocks. In the 8 mode conditions a block was an arbitrary subgroup of the 34 transitions, consisting of 11 or 12 different transitions. Again the transition order was randomized for difficulty.

The second session under the same conditions consisted of the other 6 pairs for 2 modes, and the same 3 blocks in the opposite order for 4 and 8 mode conditions. The order of the blocks in the first session varied with the subject. At the end, each subject had had 2 examples of each transition under all conditions.

The order in which the subjects were given the various conditions is summarized in the table below. The numbers represent the number of modes in a given session for a particular subject.

	PURSUIT				COMPENSATORY							PURSUIT		
Session		1	2	3		4	5	6	7	8	9	10	11	12
Subj: 1,3,4	Practice	4	8	8	Practice	2	2	4	4	8	8	2	2	4
Subj: 2,5	Practice	4	2	2	Practice	8	8	4	4	2	2	8	8	4

Before the compensatory runs, the subjects were told what the differences were from the pursuit display and given practice on each of the 8 gains amounting to a total of at least 40 minutes.

Measurement. Fig. B.1 shows the way in which results were measured. Tracking performance was recorded on a four-channel pen recorder. The upper record is input signal and subject's response. The second record shows the input and the alternate response channel, so that the "response" is what the subject's response would be if he were still tracking under pre-transition conditions. The third record is the subject's error, (response-input) and the fourth channel shows integrated absolute error over 1/4 sec. The scale for the latter is 1 cm = 1 inch steady-state error.

These records were used to determine adjustment time. This measure is an attempt to represent the time at which the subject has recovered from the effects of the transition and is tracking normally. Since the criterion for good tracking depends not only on the subject and whether he was tracking under pursuit or compensatory conditions, but also on the final gain condition, separate criterion values were used for each final gain condition.

A criterion level was found as follows. Two examples of asymptotic tracking for the particular subject and condition were examined and the median integrated absolute error over 10 secs. was found for each. The average of these two was then multiplied by 3. The adjustment time was taken as the time at which the integrated absolute error went below this value and stayed there for at least 3 sec.

In the example shown for S4 tracking under a gain of +1 with a pursuit display (Fig. B.I) the median asymptotic level is 2.8 mm (or 0.28 inch on the screen). The criterion then is 8.5 mm. Looking at the record it can be seen that 0.7 sec. following the $-4 \rightarrow +1$ transition the error falls below this point and stays there for more than 3 secs. Thus 0.7 sec. is the adjustment time in this case.

B.2 Average Error Computation

Inspection of individual transition response records corresponding to changes in controlled element dynamics often shows great variation in the characteristics of adaptation to the new mode of control. Part of this difficulty may be ascribed to the input signal which contributed to the error, and part to variation in individual subjects' adaptation characteristics. To expose consistencies in the adaptation process, we compute the ensemble average error waveform following a given type of control transition, using the PDP-1 digital computer for the computation. The experimental procedure is essentially the same as described above. Following a practice session, the subject would track through two experimental runs of 24 transitions each. The average error computation was performed on 20 error waveforms following each type of transition. Except where otherwise indicated, the transitions were of the two-mode type, that is, back and forth between the two selected modes of control.

Aspects of errors following transition not closely associated with the adaptation process will cancel out on the average. That portion of error strongly dependent upon the input signal and the relation between time of permissible transitions and velocity of the input may be compensated for by computation of the average error occurring when Channels 1 and 2 are in identical control modes so that the transitions involve no change whatsoever in the operator's observed controlled element characteristics. By subtracting out the "no transition" average response from the average error waveform curves we achieve the "compensated" average error waveforms which presumably show the nature of the adaptation process independent of the waveform of the input signal. The compensating process is illustrated by Fig. B.2. Fig. B.2a is the average error waveform following a transition from +2 to -8 in compensatory tracking with the R.64 spectrum. Notice the rapid buildup of a large error in the first second following the transition of the controlled element gain from +2 to -8, and the continuation of a smaller, but not negligible, average error during the entire five seconds of the record. Although the initial portion of this curve gives considerable interesting information on the time course of the error following the transition, it is difficult to say when the error is reduced to its asymptotic level, or indeed what the asymptotic error is. Fig. B.2b, the average error waveform taken under the same tracking conditions but with transitions from +2 to +2, shows the portion of the average error which can be attributed to the input spectrum and non-random time of transitions with respect to input velocity. When the average error of Fig. B.2b is subtracted from the average error waveform of Fig. B.2a to form the compensated average error waveform of Fig. B.2c the nature of the adaptation process is more clearly shown. There is a delay of 76 msec. in the digital computer program between the occurrence of a transition and the initial error waveform sample that is averaged. This accounts for the discontinuity at the beginning of the compensated average error curves.

B.3 Step Experiments

A series of informal experiments was conducted to test the hypothesis that the time of adaptation for step input signals depends principally upon the number of input steps rather than the length of time the subject spends in tracking. For a compensatory tracking test the proportional control gain was switched between a pair of values at random time. In half the experiments the control gain was switched between the values +1 and +6; and for the other half the control gain was switched between +1 and +11. The input function was a series of steps suitably random in both time of occurrence and in amplitude. The principal variable was the average repetition rate of these steps. Two repetition rates were used: a high rate of approximately 30 steps per minute and a low rate of approximately ten steps per minute. Following each gain change the subject's response performance was measured on the next ten steps to determine the extent of adaptation.

The performance criterion was the movement time (MT) which was defined as the time taken from the beginning of a corrective action (just after the reaction time) until the error and error rate were reduced below some arbitrary threshold. The error threshold was selected at 5 percent of the average amplitude of the input steps (0.1 inch) and the velocity threshold was 0.5 inch per sec.

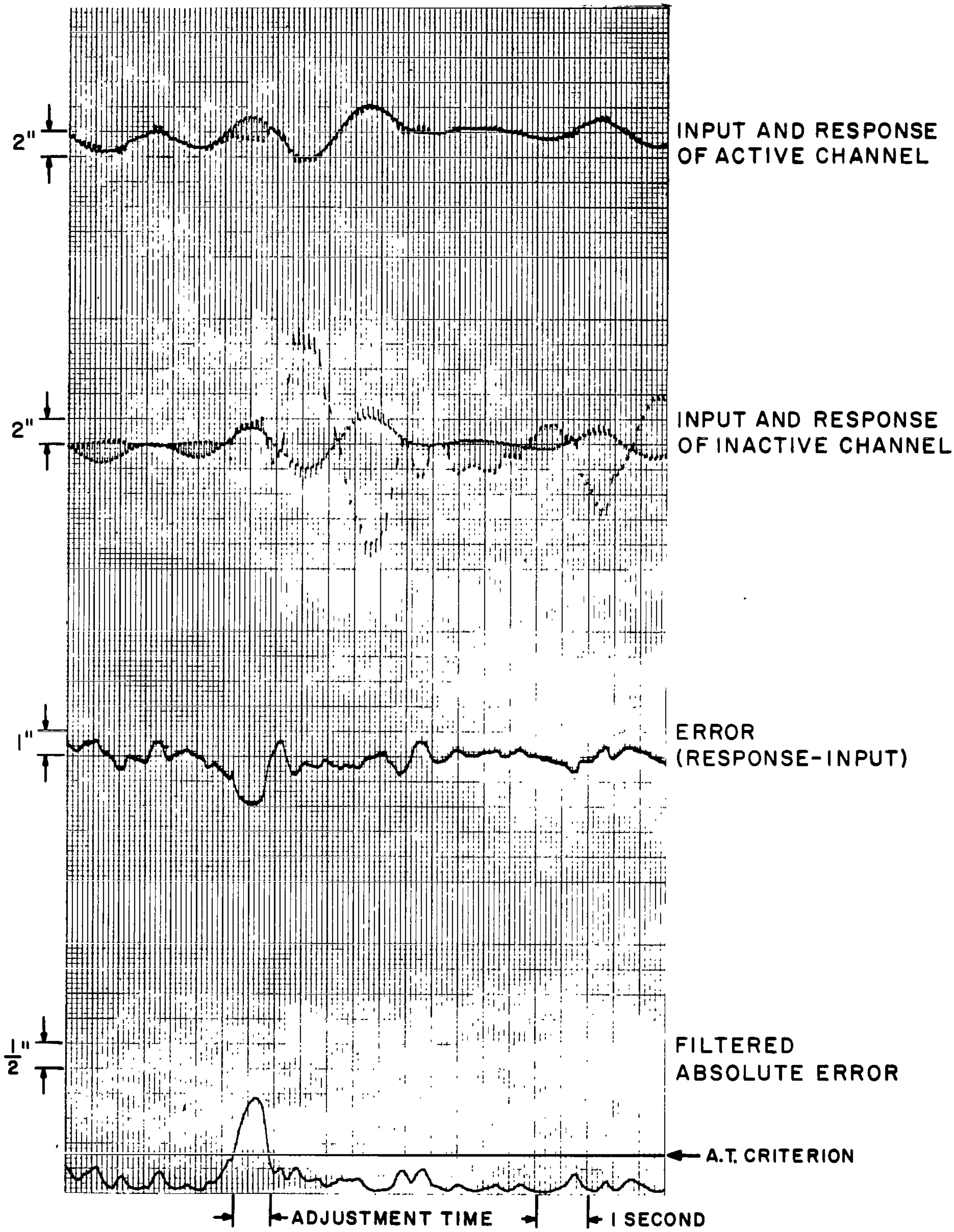

FIG. B-1 TIME TRACING FOLLOWING A TRANSITION
SUBJECT 4, 2 MODES, PURSUIT, (R · 64), -4 → +1

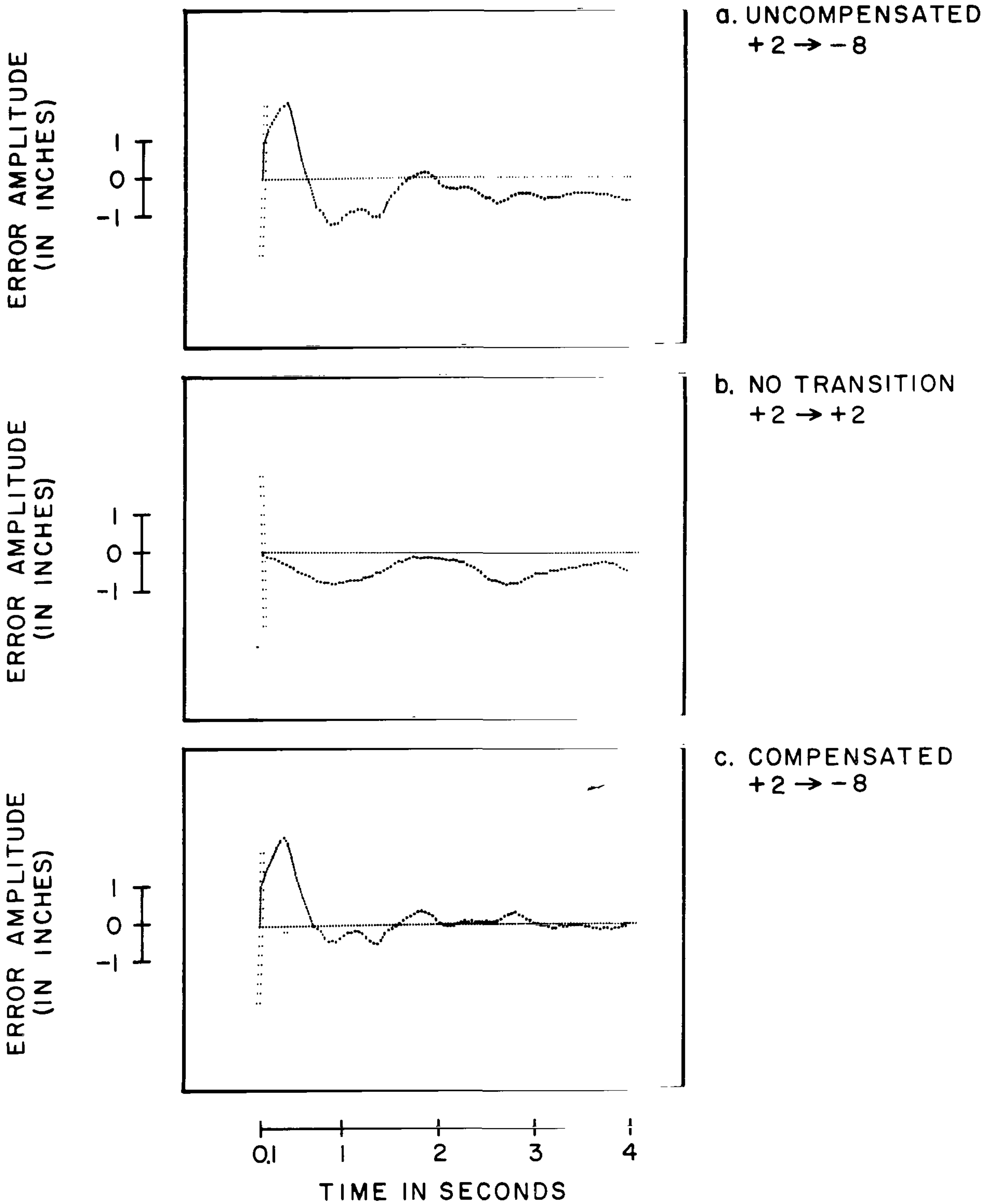

FIG. B-2 AVERAGE ERROR WAVEFORMS SHOWING THE EFFECT OF COMPENSATING FOR THE "NO TRANSITION" CHARACTERISTICS
SUBJECT LRY, 2 MODES, COMPENSATORY, (R·64)

APPENDIX C

ADJUSTMENT TIME DATA

TABLE C1

ADJUSTMENT TIME EXPERIMENT
RAW DATA

PURSUIT - 2 MODES

TYPE	TRANSITION		RD	S1		S2		S3		S4		S5		SUM
GAIN INCREASE	+1	+8	7	--		--		--		--		--		--
	+1	+4	3	2.5	5.2	16.0	2.9	2.3	2.1	1.1	7.3	0.4	1.1	40.9
	-2	-8	3	1.3	0.9	1.1	3.7	1.3	0.8	3.4	15.0	0	1.2	28.7
	-1	-4	3	--		--		--		--		--		--
	-1	-2	1	0.6	0.6	1.1	5.0	7.7	0.8	1.7	3.9	0	1.4	22.8
	+4	+8	1	6.4	15.0	2.8	0.6	0.5	1.9	2.4	1.1	0.6	0.5	31.8
	+1	+2	1	--		--		--		--		--		--
	-2	-4	1	--		--		--		--		--		--
GAIN DECREASE	+8	+1	7/8	--		--		--		--		--		--
	+4	+1	3/4	4.8	6.4	9.6	0.6	2.7	10.3	0.8	1.5	1.3	4.2	42.2
	-8	-2	3/4	0	2.0	12.6	2.1	1.9	0.6	0	3.0	0	0	22.2
	-4	-1	3/4	--		--		--		--		--		--
	-2	-1	1/2	8.3	14.3	14.1	0.5	0	0	0	0	0.8	0	38.0
	+8	+4	1/2	0	15.0	0.6	0	0.7	2.4	6.8	3.1	0	0.7	29.3
	+2	+1	1/2	--		--		--		--		--		--
	-4	-2	1/2	--		--		--		--		--		--
REVERSAL	+2	-2	2	1.7	0.9	7.0	0.9	7.8	8.7	1.0	1.3	0.7	1.4	31.4
	-2	+4	2	2.1	7.5	7.3	5.1	3.2	6.6	0.4	1.5	1.8	1.4	36.9
	+4	-4	2	3.5	4.2	3.4	1.0	0.8	1.9	1.3	1.5	0.8	0.8	19.2
	-4	+4	2	6.9	2.4	2.1	1.3	1.2	1.0	5.3	1.6	1.5	1.7	25.0
REVERSAL INCREASE	+1	-8	9	2.2	2.0	8.5	6.3	1.7	4.3	3.4	1.9	2.7	2.6	35.6
	-1	+8	9	2.9	3.8	6.7	6.8	2.9	2.0	3.4	2.3	10.3	2.3	43.4
	-2	+8	5	5.1	4.1	11.0	5.9	2.5	6.4	4.1	1.7	4.2	6.3	51.3
	+1	-4	5	5.9	2.7	10.0	18.3	1.4	0.4	12.9	3.0	1.3	2.1	58.0
	+2	-8	5	--		--		--		--		--		--
	-4	+8	3	8.1	15.0	1.2	9.1	0.6	1.3	1.5	0.8	4.4	7.3	49.3
	+1	-2	3	1.1	0	0.9	1.1	1.0	6.7	4.3	1.7	0.9	0.5	18.2
REVERSAL DECREASE	-8	+1	1-1/8	1.8	0.8	1.0	1.2	2.3	1.5	2.2	2.6	2.3	1.5	17.2
	+8	-1	1-1/8	2.2	1.5	15.0	7.4	1.9	2.0	1.0	0.9	0.7	2.2	34.8
	+8	-2	1-1/4	1.5	2.0	8.6	2.1	1.5	1.5	0.9	0.8	2.8	1.0	22.7
	-4	+1	1-1/4	6.9	1.2	3.5	5.3	3.2	6.2	0.7	19.3	0	2.1	48.4
	-8	+2	1-1/4	--		--		--		--		--		--
	+8	-4	1-1/2	14.1	7.2	6.4	4.4	1.9	0.8	1.8	0.8	3.1	0.6	41.1
	-2	+1	1-1/2	1.6	10.0	4.3	1.1	1.2	2.9	1.0	2.6	0.6	2.2	27.5

TABLE C2
ADJUSTMENT TIME EXPERIMENT
RAW DATA

PURSUIT - 4 MODES

TYPE	TRANSITION		RD	S1		S2		S3		S4		S5		SUM
GAIN INCREASE	+1	+8	7	14.1	1.6	2.6	5.5	1.4	4.0	2.6	3.3	1.8	16.3	53.2
	+1	+4	3	7.5	5.4	1.7	2.7	1.1	4.7	1.0	0.8	0.8	0.7	26.4
	-2	-8	3	1.0	13.2	7.0	2.1	6.0	1.7	6.3	1.1	0.8	4.4	43.6
	-1	-4	3	1.4	14.3	2.0	1.4	1.0	1.6	1.3	1.3	0.8	3.4	28.5
	-1	-2	1	0	4.9	1.8	2.4	1.8	0	3.9	0	0	0	14.8
	+4	+8	1	8.8	0.7	4.6	7.3	1.6	0.5	2.5	0	0.4	1.5	27.9
	+1	+2	1	1.4	2.7	18.4	1.6	4.3	2.8	1.0	0.9	0	0.6	33.7
	-2	-4	1	3.0	1.8	15.0	12.0	2.2	5.6	0.6	9.2	0	1.8	51.2
GAIN DECREASE	+8	+1	7/8	7.7	4.3	10.2	4.0	2.1	1.8	6.4	0.8	3.1	2.3	42.7
	+4	+1	3/4	2.0	0	1.8	1.3	1.0	8.1	1.8	1.6	0.7	0.5	18.8
	-8	-2	3/4	0.7	16.5	15.3	1.4	0.6	0.4	1.4	0.8	0	1.3	38.4
	-4	-1	3/4	1.6	1.5	15.0	2.9	0	1.3	2.0	1.5	1.5	0.7	28.0
	-2	-1	1/2	0.6	0	5.1	10.2	1.5	2.0	1.2	0.5	1.4	2.8	25.3
	+8	+4	1/2	6.4	0.4	3.9	1.5	0.7	0	4.8	0	0.7	1.4	19.8
	+2	+1	1/2	2.1	7.3	5.5	0.5	0	3.1	0.1	0	0	1.3	19.9
	-4	-2	1/2	0.4	1.4	4.2	2.5	0	0	0.7	0	0	0	9.2
REVERSAL	+2	-2	2	2.1	1.7	1.4	1.5	1.8	1.4	2.5	0.6	2.7	6.1	21.8
	-2	+4	2	1.8	15.0	1.3	9.5	4.6	3.1	5.0	0.7	1.0	0.8	42.8
	+4	-4	2	2.0	1.7	3.0	1.2	8.8	1.1	5.6	1.0	0	1.0	25.4
	-4	+4	2	5.6	4.2	5.7	1.4	1.5	1.5	11.3	1.0	2.1	3.7	38.0
REVERSAL INCREASE	+1	-8	9	6.6	15.0	14.5	2.2	1.5	0.9	4.5	4.2	3.0	2.0	54.4
	-1	+8	9	3.7	37.0	10.0	5.2	7.7	5.0	2.8	5.4	3.8	13.9	94.5
	-2	+8	5	8.6	4.6	2.0	8.3	8.1	5.1	2.0	0.9	4.8	5.2	49.6
	+1	-4	5	13.2	1.0	15.0	1.2	2.7	4.8	1.6	1.0	1.5	6.5	48.5
	+2	-8	5	11.4	21.8	2.2	7.5	1.4	2.1	4.4	1.0	1.7	14.0	67.5
	-4	+8	3	5.2	1.2	8.3	1.9	3.5	5.4	3.8	4.3	4.0	6.4	44.0
	+1	-2	3	1.5	15.0	12.5	12.6	1.3	7.7	5.8	1.8	1.3	2.1	61.6
REVERSAL DECREASE	-8	+1	1-1/8	3.0	15.0	5.4	20.6	4.0	2.1	1.0	1.4	1.1	4.4	58.0
	+8	-1	1-1/8	4.8	19.7	23.0	9.4	0.5	0.9	2.4	0.8	3.5	1.9	66.9
	+8	-2	1-1/4	5.2	1.8	3.7	0.9	2.0	3.6	4.4	2.5	3.0	4.2	31.3
	-4	+1	1-1/4	15.3	1.0	18.3	1.1	3.9	1.9	14.0	0.9	3.0	2.2	61.6
	-8	+2	1-1/4	7.2	2.7	3.1	11.0	15.0	8.6	6.6	1.7	0.9	12.8	69.6
	+8	-4	1-1/2	9.1	6.4	2.2	6.6	1.4	1.1	2.2	7.4	2.7	2.1	41.2
	-2	+1	1-1/2	2.5	15.0	1.1	2.9	6.0	6.5	2.6	1.2	0.9	2.6	41.3

TABLE C3

ADJUSTMENT TIME EXPERIMENT
RAW DATA

PURSUIT - 8 MODES

TYPE	TRANSITION		RD	S1		S2		S3		S4		S5		SUM.
GAIN INCREASE	+1	+8	7	6.8	3.7	1.5	7.2	8.0	7.0	21.2	2.5	4.0	3.9	65.8
	+1	+4	3	2.6	1.2	2.4	8.1	3.0	1.3	1.6	1.6	4.0	4.6	30.4
	-2	-8	3	34.1	1.9	4.8	1.6	2.0	5.3	0.8	0.8	8.8	10.9	71.0
	-1	-4	3	7.9	2.2	4.0	3.1	4.0	2.2	0.8	3.4	0	1.0	28.6
	-1	-2	1	15.0	0.6	3.1	0.8	1.8	1.3	15.7	3.0	0.5	20.2	62.0
	+4	+8	1	0.6	1.9	2.9	1.2	2.8	1.2	15.0	0	6.0	13.5	45.1
	+1	+2	1	3.3	1.9	2.7	15.0	0.9	0	6.2	5.7	0.5	4.4	40.6
	-2	-4	1	0.6	0.5	3.4	4.6	0.6	0	15.7	15.4	3.4	3.4	47.6
GAIN DECREASE	+8	-1	7/8	9.2	0.9	13.4	10.0	3.2	1.0	1.8	8.9	0.8	1.9	51.1
	+4	+1	3/4	4.6	6.2	1.7	2.1	3.0	5.3	3.6	0.7	1.3	5.9	34.8
	-8	-2	3/4	5.2	0.4	14.0	19.5	0.5	1.7	8.2	4.4	5.3	1.5	60.7
	-4	-1	3/4	1.6	6.0	2.5	2.9	2.8	3.1	0.8	1.9	1.0	1.4	24.0
	-2	-1	1/2	3.3	2.9	9.4	0	1.0	0	0	0	1.7	7.2	25.5
	+8	+4	1/2	3.2	0.3	1.3	1.1	2.8	0	2.3	4.3	1.4	0.5	17.2
	+2	+1	1/2	10.3	0.6	2.0	0.9	3.1	1.5	0.7	0	3.5	0.5	23.1
	-4	-2	1/2	5.9	0.9	0	0	4.2	0	5.1	0.7	1.0	4.8	22.6
REVERSE	+2	-2	2	8.1	1.5	5.0	7.3	1.4	1.6	1.8	6.8	3.2	1.4	38.1
	-2	+2	2	5.8	1.4	1.0	2.2	4.4	5.3	8.9	2.0	1.8	6.7	39.5
	+4	-4	2	10.5	1.7	9.8	1.3	1.6	6.0	18.2	12.6	0.7	2.2	64.6
	-4	+4	2	15.0	1.1	1.3	4.6	2.3	6.4	4.2	2.3	3.7	2.2	43.1
REVERSE INCREASE	+1	-8	9	12.2	8.6	18.0	2.3	2.8	1.9	7.8	1.5	19.2	1.2	75.5
	-1	+8	9	4.0	2.1	6.1	4.5	3.6	3.9	25.7	8.2	10.7	12.5	81.3
	-2	+8	5	2.1	2.6	3.0	0.9	6.6	9.0	1.8	5.7	6.6	15.6	53.9
	+1	-4	5	1.3	6.3	4.8	8.6	9.5	1.5	12.4	1.2	4.1	2.9	52.6
	+2	-8	5	2.5	1.6	6.8	14.5	1.3	3.0	3.4	2.3	2.9	0.9	39.2
	-4	+8	3	15.0	1.5	8.6	1.0	2.2	14.0	3.5	3.5	2.0	15.0	66.3
	+1	-2	3	1.3	1.4	15.9	12.8	1.5	1.6	1.5	2.9	1.4	1.3	41.6
REVERSE DECREASE	-8	+1	1-1/8	5.2	1.2	7.5	22.6	2.7	5.8	1.4	1.4	3.3	1.7	52.8
	+8	-1	1-1/8	1.9	4.5	5.5	5.9	2.7	1.9	3.6	1.8	3.3	2.6	33.7
	+8	-2	1-1/4	2.3	1.4	11.9	9.3	3.4	1.9	3.0	2.3	2.0	0	37.5
	-4	+1	1-1/4	1.3	0	4.7	3.8	2.2	1.9	1.3	2.1	5.0	6.4	28.7
	-8	+2	1-1/4	1.3	1.4	1.7	10.1	4.4	8.5	15.1	1.3	1.3	1.3	46.4
	+8	-4	1-1/2	7.2	1.9	1.9	12.0	1.4	3.1	14.5	1.3	4.9	3.4	51.6
	-2	+1	1-1/2	7.4	1.3	2.0	1.8	10.7	10.0	3.9	0.9	2.0	3.4	43.4

TABLE C4
ADJUSTMENT TIME EXPERIMENT
RAW DATA

COMPENSATORY - 2 MODES

TYPE	TRANSITION		RD	S1		S2		S3		S4		S5		SUM.
GAIN INCREASE	+1	+8	7											
	+1	+4	3	2.0	8.4	1.5	2.6	1.7	2.5	0.8	7.9	15.7	4.4	47.5
	-2	-8	3	0.6	1.9	4.2	3.0	2.6	12.6	2.6	7.4	3.4	5.9	44.2
	-1	-4	3											
	-1	-2	1	2.9	4.1	2.6	0	0	6.6	2.6	1.2	1.9	1.7	23.6
	+4	+8	1	3.1	2.3	0.3	1.9	0	0.8	5.3	1.2	3.0	0.5	18.4
	+1	+2	1											
	-2	-4	1											
GAIN DECREASE	+8	+1	7/8											
	+4	+1	3/4	7.5	1.9	8.4	11.9	0	2.0	1.2	2.1	4.2	7.0	46.2
	-8	-2	3/4	5.5	3.5	10.6	11.2	4.8	0	2.5	6.8	0.6	2.0	47.5
	-4	-1	3/4											
	-2	-1	1/2	0	2.4	0.5	2.8	0	0.5	3.5	5.7	2.6	0	18.0
	+8	+4	1/2	4.9	1.6	2.6	10.1	0.3	0.5	16.4	6.6	0	0.7	43.7
	+2	+1	1/2											
	-4	-2	1/2											
REVERSAL	+2	-2	2	4.6	8.0	2.5	1.9	2.7	4.7	4.4	0.9	1.0	4.3	35.0
	-2	+4	2	5.2	1.2	8.1	4.1	2.5	1.6	8.3	1.1	1.9	4.5	38.5
	+4	-4	2	5.8	8.9	3.6	2.7	1.5	3.2	3.3	17.5	4.3	1.9	52.7
	-4	+4	2	2.6	3.5	0.7	3.2	3.0	2.6	16.9	10.3	3.4	2.2	48.4
REVERSAL INCREASE	+1	-8	9	4.0	5.9	1.3	1.3	1.4	3.9	14.3	7.1	3.9	3.2	46.3
	-1	+8	9	8.3	1.6	1.5	2.4	1.7	1.9	3.1	2.1	11.7	3.1	37.4
	-2	+8	5	2.6	8.5	0.6	2.5	3.6	17.5	5.8	3.1	4.5	2.1	50.8
	+1	-4	5	6.6	1.5	2.9	1.8	1.5	1.9	9.5	1.0	1.0	1.6	29.3
	+2	-8	5											
	-4	+8	3	4.2	9.4	9.2	1.0	4.1	3.1	4.0	3.4	2.9	2.2	43.5
	+1	-2	3	11.0	8.8	4.0	3.3	7.0	3.3	7.9	6.8	1.6	5.0	58.7
REVERSAL DECREASE	-8	+1	1-1/8	9.1	6.8	11.7	10.2	10.7	8.3	8.4	9.2	11.3	8.4	94.1
	+8	-1	1-1/8	5.4	5.1	2.9	1.1	2.2	5.8	1.8	6.8	5.4	2.7	39.2
	+8	-2	1-1/4	4.1	3.9	3.3	3.4	7.1	5.8	13.3	3.4	1.5	3.2	49.0
	-4	+1	1-1/4	6.3	1.4	30.0	1.1	6.6	11.7	9.2	5.1	1.2	1.4	74.0
	-8	+2	1-1/4											
	+8	-4	1-1/2	12.8	3.5	4.5	9.6	1.5	1.6	1.0	3.7	2.5	3.7	44.4
	-2	+1	1-1/2	6.0	3.3	4.3	7.4	7.3	9.6	7.1	6.3	6.1	2.3	59.7

TABLE C5
ADJUSTMENT TIME EXPERIMENT
RAW DATA

COMPENSATORY - 4 MODES

TYPE	TRANSITION		RD	S1		S2		S3		S4		S5		SUM.
GAIN INCREASE	+1	+8	7	3.0	4.8	0.9	0.7	2.9	4.5	5.5	1.9	5.5	3.2	32.9
	+1	+4	3	1.6	1.0	1.9	1.5	0	4.6	2.2	3.2	1.7	0.8	18.5
	-2	-8	3	4.1	5.7	2.1	2.9	5.8	6.4	20.2	5.4	7.4	1.9	61.9
	-1	-4	3	2.5	3.7	8.1	9.0	4.2	1.0	0.8	13.6	1.7	1.9	46.5
	-1	-2	1	7.4	6.8	1.8	0	0	0	0	4.2	4.2	6.4	30.8
	+4	+8	1	4.5	14.2	4.7	1.3	0	1.0	3.0	0	1.4	3.0	33.1
	+1	+2	1	1.2	1.5	2.3	3.2	2.7	1.0	1.1	0	4.0	0	17.0
	-2	-4	1	27.1	14.7	0	3.1	0	0	12.9	0.6	3.0	3.1	64.5
GAIN DECREASE	+8	+1	7/8	3.7	3.4	5.9	17.3	11.1	6.6	0.9	15.3	3.9	6.3	74.4
	+4	+1	3/4	2.7	6.7	20.9	18.8	4.9	2.4	0	5.7	8.2	5.6	75.9
	-8	-2	3/4	3.0	3.4	0.7	4.4	10.5	0	1.0	5.0	4.7	9.0	41.7
	-4	-1	3/4	0	2.9	0	4.6	6.8	4.5	1.0	0.5	0.7	0.6	21.6
	-2	-1	1/2	10.3	1.1	0.7	2.9	2.0	3.3	0.5	0	7.7	0	28.5
	+8	+4	1/2	0	0	0	0	0	3.2	6.2	0.1	2.1	3.1	14.7
	+2	+1	1/2	1.1	0.4	3.3	2.9	0.8	0	4.8	3.5	10.9	4.1	31.8
	-4	-2	1/2	0.1	0.6	2.3	0	2.1	1.5	6.9	3.6	3.7	0	20.8
REVERSAL	+2	-2	2	1.0	3.9	1.6	2.8	0.5	1.4	0.6	9.6	1.1	1.1	23.6
	-2	+4	2	4.0	2.5	9.0	1.4	1.9	6.6	0.9	2.2	0.7	4.5	33.7
	+4	-4	2	9.5	16.5	6.1	2.0	1.1	1.8	10.8	1.4	1.2	3.4	53.8
	-4	+4	2	5.5	9.4	12.0	1.1	12.5	2.3	2.2	1.7	12.4	1.8	60.9
REVERSAL INCREASE	+1	-8	9	2.6	1.7	2.1	1.0	4.9	9.7	3.9	10.8	2.4	8.3	47.4
	-1	+8	9	4.0	10.6	1.2	5.6	4.5	4.1	5.6	9.9	11.7	3.9	61.1
	-2	+8	5	2.1	6.0	6.0	0.9	7.5	1.7	2.5	1.5	6.7	5.1	40.0
	+1	-4	5	10.2	3.3	10.0	3.2	4.2	3.3	6.3	1.8	4.2	14.1	60.6
	+2	-8	5	1.1	4.9	2.3	1.0	4.0	10.5	12.9	13.4	4.4	5.5	60.0
	-4	+8	3	2.9	2.5	4.9	5.0	4.7	8.6	3.5	3.6	3.9	8.6	48.2
	+1	-2	3	1.9	2.7	10.3	2.4	3.1	1.6	5.0	5.1	0.8	1.1	34.0
REVERSAL DECREASE	-8	+1	1-1/8	6.6	7.8	15.0	9.6	6.3	9.0	7.7	14.0	5.2	9.1	90.3
	+8	-1	1-1/8	7.0	6.5	15.6	1.2	1.7	4.5	7.7	11.4	2.7	3.2	61.5
	+8	-2	1-1/4	0	5.2	8.9	3.1	6.4	7.0	4.7	0.1	10.2	0.8	46.4
	-4	+1	1-1/4	6.3	6.3	13.4	5.6	6.3	1.2	10.8	2.2	2.5	16.8	71.4
	-8	+2	1-1/4	6.3	2.5	7.9	16.6	3.1	2.1	3.0	3.5	5.1	1.0	51.1
	+8	-4	1-1/2	12.2	11.1	12.8	8.2	3.6	11.2	3.5	6.6	1.6	3.9	74.7
	-2	+1	1-1/2	3.5	-10.2	11.0	3.2	5.1	6.2	3.1	3.7	6.1	5.5	57.6

TABLE C6
ADJUSTMENT TIME EXPERIMENT
RAW DATA

COMPENSATORY - 8 MODES

TYPE	TRANSITION		RD	S1		S2		S3		S4		S5		SUM.
GAIN INCREASE	+1	+8	7	9.1	5.5	11.8	1.8	2.8	4.4	5.2	10.1	7.9	2.1	60.7
	+1	+4	3	2.2	3.8	3.8	1.3	6.0	0	3.5	1.6	1.8	1.5	25.5
	-2	-8	3	1.2	1.6	3.7	0	5.2	7.4	1.6	1.0	2.9	3.8	28.4
	-1	-4	3	17.0	6.3	11.9	5.4	2.2	2.1	1.2	11.7	3.2	3.3	64.3
	-1	-2	1	2.0	6.0	2.9	15.8	4.3	2.4	1.3	1.6	0.1	7.3	43.7
	+4	+8	1	0.3	4.7	0	4.9	0	5.8	6.3	2.2	10.9	4.1	39.2
	+1	+2	1	3.0	1.3	5.7	0.4	14.4	0	0.9	1.9	6.1	4.4	38.1
	-2	-4	1	7.0	1.6	2.5	0	5.2	0	10.2	11.3	0	3.9	41.7
GAIN DECREASE	+8	+1	7/8	2.6	4.6	15.0	15.0	2.7	1.6	1.0	1.5	2.5	15.4	61.9
	+4	+1	3/4	7.9	0	6.4	2.1	6.4	0.8	3.4	3.6	4.5	4.5	39.6
	-8	-2	3/4	0	1.8	0.8	0	0	0	1.9	5.4	1.2	0.3	11.4
	-4	-1	3/4	7.6	1.4	7.8	2.8	3.0	0	4.4	0.3	0.7	0.7	28.7
	-2	-1	1/2	0	0	0.5	0	0	2.7	6.5	0	6.8	2.7	19.2
	+8	+4	1/2	0	12.7	0.4	11.0	2.1	2.2	0.5	6.4	4.4	0.1	39.8
	+2	+1	1/2	0.5	0.5	15.0	5.1	10.0	4.4	0	3.9	0.7	0.3	40.4
	-4	-2	1/2	8.1	0.6	0	0	2.7	3.3	0	0.7	0.7	0.4	16.5
REVERSAL	+2	-2	2	5.2	0	4.5	2.8	2.5	1.5	1.1	1.3	15.0	0.3	34.2
	-2	+4	2	4.8	3.2	13.9	3.4	3.4	3.0	1.7	2.9	0.8	4.4	41.5
	+4	-4	2	4.7	11.2	4.3	2.4	0.8	1.1	2.3	6.4	0	1.9	35.1
	-4	+4	2	2.6	2.9	3.7	2.7	2.6	3.4	3.7	4.9	6.5	5.2	38.2
REVERSAL INCREASE	+1	-8	9	1.7	7.3	4.1	1.5	5.8	5.1	5.8	1.1	15.0	8.4	55.8
	-1	+8	9	3.7	5.9	1.1	3.7	10.0	3.4	0.9	8.7	3.5	4.5	45.4
	-2	+8	5	10.6	6.7	3.8	5.2	4.9	4.3	2.1	5.4	7.2	5.8	56.0
	+1	-4	5	9.0	3.8	12.6	1.6	2.3	9.0	4.7	2.2	0	4.0	49.2
	+2	-8	5	2.1	3.2	2.8	1.1	4.5	2.4	13.1	3.9	1.6	8.4	43.1
	-4	+8	3	0.9	1.4	9.4	3.7	2.2	6.4	0.6	4.5	9.9	3.7	42.7
	+1	-2	3	6.1	2.6	10.9	11.9	5.1	4.5	0.7	0.9	17.2	7.6	67.5
REVERSAL DECREASE	-8	+1	1-1/8	1.5	3.5	15.8	17.5	7.9	6.1	4.1	6.3	15.0	8.9	86.6
	+8	-1	1-1/8	5.9	5.8	4.4	3.9	15.8	11.1	5.9	2.0	8.9	9.1	72.8
	+8	-2	1-1/4	8.0	4.9	5.9	15.0	2.7	3.8	4.1	2.1	2.4	5.4	54.3
	-4	+1	1-1/4	6.7	7.5	15.0	20.9	8.6	12.9	1.4	4.1	15.0	5.6	97.7
	-8	+2	1-1/4	3.8	2.2	11.1	16.6	4.7	3.6	10.5	0.8	9.7	2.9	65.9
	+8	-4	1-1/2	16.5	4.8	9.2	7.1	1.7	2.3	6.5	10.1	4.1	5.4	67.7
	-2	+1	1-1/2	5.8	1.6	15.0	15.0	2.8	2.0	1.6	2.9	8.7	4.1	59.5

TABLE C7

ADJUSTMENT TIME EXPERIMENT

SUMMARY OF DATA

DISPLAY MODES		PURSUIT 2	PURSUIT 4	PURSUIT 8	COMPENSATORY 2	COMPENSATORY 4	COMPENSATORY 8
	Sum	216.5	445.2	292.2	232.5	372.3	299.0
S1	Mean	4.5	6.2	4.3	4.8	5.2	4.4
	Median	2.6	3.35	2.25	4.15	3.7	3.6
	Sum	247.5	430.1	388.2	222.3	380.8	437.3
S2	Mean	5.2	6.0	5.7	4.6	5.3	6.4
	Median	4.0	3.4	3.9	2.9	3.1	4.2
	Sum	125.3	212.9	226.6	185.8	296.1	278.3
S3	Mean	2.6	3.0	3.3	3.9	4.1	4.1
	Median	1.9	1.8	2.7	2.6	3.3	3.15
	Sum	140.6	197.4	344.9	279.9	344.1	252.4
S4	Mean	2.9	2.7	5.1	5.8	4.8	3.7
	Median	1.7	1.6	2.7	5.2	3.5	2.6
	Sum	86.3	199.0	287.6	169.6	318.4	345.3
S5	Mean	1.8	2.8	4.2	3.5	4.4	5.1
	Median	1.3	1.85	3.05	2.8	3.8	4.1
	Sum	816.2	1484.6	1539.5	1090.1	1711.7	1612.3
Total	Mean	3.4	4.1	4.9	4.5	4.8	4.7
	Median	2.0	2.1	2.8	3.3	3.5	3.7

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TABLE C8

MEDIAN ADJUSTMENT TIMES FOR TRANSITIONS

TYPE OF TRANSITION	PURSUIT	COMPENSATORY
Gain Inc.	2.15	2.85
Gain Dec.	1.5	2.55
Reverse	2.0	2.9
Reverse Inc.	3.65	3.95
Reverse Dec.	2.35	5.85

RELATIVE DIFFERENCES	PURSUIT	COMPENSATORY
9	3.95	3.9
5	4.1	3.95
3	2.1	3.45
2	2.0	2.9
1-1/2	2.6	5.25
1-1/4	2.4	5.1
1-1/8	2.25	6.8
1	1.8	2.45
3/4	1.7	2.95
1/2	0.95	1.3

2/7/85
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